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JUN 78 V D SMITH, C M TELLER, R K SWANSON F41608-77-C-1381

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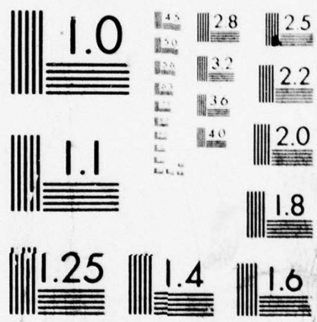

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ENGINEERING SERVICES TO DETERMINE ACCEPTANCE LIMITS OF ULTRASONIC TRANSDUCERS FOR NONDESTRUCTIVE INSPECTION

FINAL ENGINEERING REPORT

Contract No. F41608-77-C-1381
SwRI Project No. 15-5024

June 1978

SOUTHWEST RESEARCH INSTITUTE
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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Electrical, ultrasonic, and flaw response performance were characterized for 23 ultrasonic transducers used by the Air Force to inspect aircraft components. Wide variation was noted in the response of these transducers to sample flaws, including a flat-bottom hole, an Elox notch, and two laboratory generated fatigue cracks. Seventeen parameters descriptive of the characteristics of these transducers were defined and

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correlations between these parameters and the flaw detection performance analyzed. Good correlation between loop sensitivity and ability to detect the sample flaws was shown for each transducer in the set. Other parameters of significance appear to be transducer center frequency, beamwidth spectrum inflection, and beam inflection. Definitions of these parameters are presented. A performance rating based on the significant parameters was developed, and, on the basis of this rating, only two of the 23 transducers were judged to be good and eleven fair. In the case of fatigue cracks the response of individual transducers ranged from signals several times the noise background permitting easy crack detection and a transducer rating of good to no signal which means the crack would not be detected and a transducer rating of poor. Establishment of certification criteria based on simple transducer loop sensitivity measurement is suggested. Additional work recommended includes verification of this proposed certification criteria based on a larger, more representative sample of transducers.

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ENGINEERING SERVICES TO DETERMINE ACCEPTANCE LIMITS OF ULTRASONIC TRANSDUCERS FOR NONDESTRUCTIVE INSPECTION

by
V. Devon Smith
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Robert K. Swanson

FINAL ENGINEERING REPORT

Contract No. F41608-77-C-1381
SwRI Project No. 15-5024

The investigation reported in this document was requested by the NDI Program Manager, MMETP, San Antonio ALC; Kelly Air Force Base, Texas 78241, under Government Contract No. F41608-77-C-1381; however, it does not necessarily bear the endorsement of the requesting agency.

September 1977 to June 1978

Approved:

John R. Barton

John R. Barton, Vice President
Instrumentation Research Division

FOREWORD

This report was prepared by Mr. V. D. Smith, Project Engineer, Dr. C. M. Teller, Project Manager, and Mr. R. K. Swanson of the Instrumentation Research Division, Southwest Research Institute, San Antonio, Texas. The support rendered by Messrs. J. T. McElroy and K. F. Briers of the Quality Assurance Systems and Engineering Division at SwRI is gratefully acknowledged. Also, the technical assistance performed by Mr. T. C. Doss of the Instrumentation Research Division is appreciated.

A special acknowledgement is due Dr. H. H. Chaskelis of the Naval Research Laboratory, Washington, D. C., for his kind permission to use several of the definitions of ultrasonic transducer performance parameters which appear in Appendix D.

The work was sponsored by San Antonio Air Logistics Center, Kelly Air Force Base, Texas, under Contract No. F41608-77-C-1381. Technical direction was provided by Messrs. B. W. Boisvert, C. L. Garcia, and J. A. Petru. The period of performance was from 13 September 1977 to 30 June 1978.

ABSTRACT

Electrical, ultrasonic, and flaw response performance were characterized for 23 ultrasonic transducers used by the Air Force to inspect aircraft components. Wide variation was noted in the response of these transducers to sample flaws, including a flat-bottom hole, an Elox notch, and two laboratory generated fatigue cracks. Seventeen parameters descriptive of the characteristics of these transducers were defined and correlations between these parameters and the flaw detection performance analyzed. Good correlation between loop sensitivity and ability to detect the sample flaws was shown for each transducer in the set. Other parameters of significance appear to be transducer center frequency, beamwidth, spectrum inflection, and beam inflection. Definitions of these parameters are presented. A performance rating based on the significant parameters was developed,and, on the basis of this rating, only two of the 23 transducers were judged to be good and eleven fair. In the case of fatigue cracks, the response of individual transducers ranged from signals several times the noise background permitting easy crack detection and a transducer rating of good to no signal which means the crack would not be detected and a transducer rating of poor. Establishment of certification criteria based on simple transducer loop sensitivity measurement is suggested. Additional work recommended includes verification of this proposed certification criteria based on a larger, more representative sample of transducers.

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I. SUMMARY

Twenty-three ultrasonic transducers obtained from the San Antonio Air Logistics Center were characterized by measurement of electrical, ultrasonic, and flaw response characteristics. Seventeen parameters were derived from these measurements and correlation analyses performed in an attempt to establish a basis for specification of transducers to produce predictable flaw response performance.

The results of this investigation showed that variability was high among the transducers in their response to the same sample flaws. For a given transducer good correlation between the flaw response and loop sensitivity was shown to exist. Loop sensitivity is a measurable characteristic of a transducer and appears to offer a reasonable basis for the prediction of individual transducer performance in the detection of small flaws. Determination of absolute values of loop sensitivity for adequate specification purposes was beyond the scope of this program. However, development of baseline reference standards and establishment of adequate controls appear to be feasible.

Other physical characteristics of transducers which appear to have reasonable correlation with flaw response include center frequency, beamwidth, spectral inflection, and beam inflection. Using accepted statistical methods, a performance rating was established for the transducers based on the loop sensitivity and these four parameters. Of the 23 transducers examined, only two were judged good, eleven fair, and ten poor by this rating methodology.

Prediction of flaw response performance of individual transducers based on measurable parameters appears to be a reasonable goal.

II. INTRODUCTION

The San Antonio Air Logistics Center (SA-ALC) at Kelly AFB has overall management responsibility for the Air Force nondestructive inspection (NDI) program, and ultrasonic (UT) inspection comprises a major part of this responsibility. One of the most critical elements of any UT inspection system is the transducer. It serves as the link between the electronic inspection instrumentation and any mechanical defects in the aircraft component under inspection and performs the dual function of producing and monitoring the ultrasonic pulses. Thus, an understanding of any distortions introduced by the transducer is critical to the interpretation of inspection results.

Wide variation in the performance of commercially available ultrasonic transducers has been noted by a number of observers.[1, 2]* The purpose of the program reported in this document was to characterize a readily available number of commercial transducers of various types presently in use in Air Force UT inspection. Correlation of parameters descriptive of the characteristics of individual transducers with their performance in detecting flaws of several types was examined. The objective of the correlations was to determine the effect of these parameters (which might form a rational basis for specification) on the reliability of UT inspection procedures used to detect small fatigue cracks in the examination of Air Force components.

The scope of the program included measurement of electrical, ultrasonic, and flaw detection characteristics of 23 transducers, and the derivation of 17 descriptive parameters from these measurements. Performance in detecting flaws was limited to longitudinal-wave examination of a flat-bottom hole standard, an Elox notch, and two cyclically generated fatigue cracks. All but the first of these were produced during the course of a previous program and reported in an earlier, separate document.[3] Details on the four flaw standards are given in Appendix A.

Ultrasonic transducers come in a variety of configurations and with varied characteristics. As shown in Figure 1, all have in common four basic parts; the outer housing the piezoelectric crystal, the wearplate, and the backing. The outer housing provides structural integrity and protection of the delicate internal components. The wearplate has the same protective function as the outer housing, but is also must transmit the ultrasonic pulses with little attenuation. The heart of the transducer is the piezoelectric crystal which produces an ultrasonic impulse when excited by an electrical impulse. The final constituent part of the transducer is the backing which is used to damp out the ringing of the

* References appear at the end of this report.

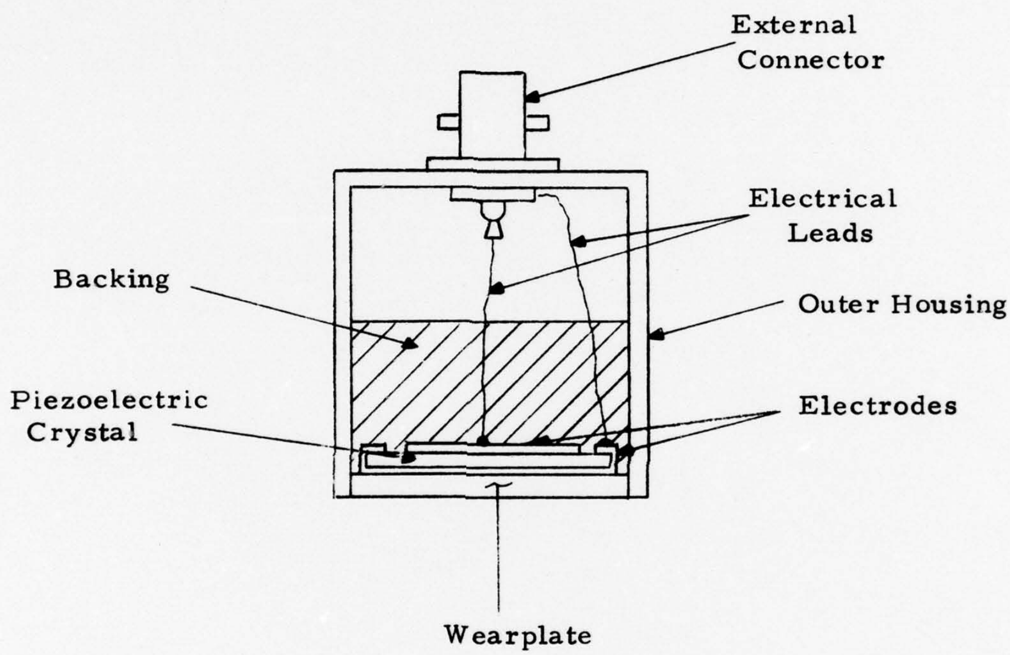

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FIGURE 1. CROSS SECTION OF TYPICAL TRANSDUCER SHOWING INTERNAL COMPONENTS

piezoelectric crystal and to absorb the ultrasound which would be radiated in the reverse direction.

A variety of materials is used in the construction of ultrasonic transducers. The outer housing is normally metallic, but can be formed of plastic. The wearplate is usually aluminum oxide, but can be any material which is acoustically matched to the crystal. The crystal itself can be natural or man-made. Quartz is the most common type of natural crystal. Man-made materials exhibit a variety of properties that can be tailored to fit a particular application. Lead metaniobate is one of the more common materials used in element fabrication. There is also a variety of backing materials, with metal powder suspended in an epoxy binder being common. The adhesive used to bond the parts together is very critical to transducer performance. In particular, the crystal-to-wearplate and backing-to-crystal bond are extremely important. An epoxy cement is generally the preferred material for this purpose.

The electrical connections in the ultrasonic transducer are also of great importance. Since a large contact area on the crystal is desirable, the crystal is generally plated with a good conductor such as gold. Copper lead wires from external connectors are then welded to the electrodes. Often an electrical tuning network is built into the transducer to insure impedance matching between the transducer and the pulser-receiver.

Although transducers appear to be simple electromechanical devices, the many sources of variability in construction create an extremely complex situation. Indeed, performance variation cannot be identified by any simple means. Thus, many different measurements, some of which are very complicated, are required to characterize the performance of any transducer.

Several measurement parameters have been used to characterize ultrasonic transducers.[4] It is not generally possible to separate the electrical properties from the ultrasonic properties, nor the response of a transducer as a transmitter from the response as a receiver. Thus, only the total system response is measured. Characteristics used to describe transducer performance include (1) RF spectrum, (2) distance-amplitude response, (3) beam profile, (4) conversion efficiency, (5) RF noise ratio, and (6) damping. All of these characteristics can be influenced by system parameters other than the transducer, so care must be taken in establishing measurement procedures.

The specification of ultrasonic transducers used in Air Force NDI is established for each particular inspection task in a document referred to as a "Technical Order" or simply T.O. A T.O. details the

selection and calibration of instrumentation as well as the technique for inspecting the particular part. Variations between ultrasonic systems of the same general type are "normalized" by adjusting reject, tuning, and gain controls on the ultrasonic pulser-receiver, using calibration standards. Standards are usually metallic blocks containing manufactured flaws of precise dimensions, designed to produce the same response in the inspection system that would be produced by an actual flaw under service conditions. However, transducer performance variability can render ambiguous calibration results.*

Many considerations are involved in the NDI of aircraft components. Some of these are unique to Air Force applications, but many are shared with other users of ultrasonic technology. Accessibility of the part to be inspected is often a major problem in aircraft, while flaw characterization is of more general concern to all users. Perhaps the most pressing problem relates to the reliability of detection. Often the question is not how small a flaw one can detect, but how large a flaw one may miss. A recent research effort designed to study the detection reliability of several typical Air Force inspection procedures[5] has documented the general conclusion that relatively large percentages of flaws are not detected during routine in-service inspections.

Thus, an assessment of the variation in performance of nominally equivalent ultrasonic transducers used in Air Force NDI was the subject of the investigation reported here. The intent of the program was to correlate the flaw response of typical transducers with other measurable characterization parameters. The acoustic radiation pattern, RF spectrum, and flaw response were measured on 23 transducers. A total of 17 separate parameters were then extracted from these data, for each transducer. Statistical variation and correlation analyses were performed with these parameters, to give an indication of the importance of transducer variability on the flaw detection capability of a UT inspection system.

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* Variability of UT inspection system performance introduced by reference standards is also recognized, but a study of this effect was beyond the scope of the present program.

III. EXPERIMENTAL PROGRAM

A. Characterization Measurements

Tests were designed to measure the electrical and ultrasonic properties of typical commercial transducers used in UT inspection in the Air Force. The ability of these transducers to detect small flaws was assessed and this performance correlated with transducer parameters which could be specified as acceptance criteria for procurement and certification.

Two classes of reference standards were used to characterize transducer response to defects: (1) artificial flaws and (2) service-type flaws. The artificial flaws consisted of a flat-bottom hole and a small notch machined by an electric discharge, generally referred to as an "Elox notch". The service-type flaws were two fatigue cracks produced by cycling 7075-T651 aluminum plate specimens under load: one a low-cycle, high load type, the other a high-cycle, low load type.

The characteristics of the transducers which were measured included (1) RF power spectrum, (2) RF waveform, (3) distance-amplitude response, (4) beam profile, (5) loop sensitivity, and (6) electrical noise.

The RF power spectrum contains all information pertaining to the frequency response of the transducer. It is produced by analyzing the waveform of a transducer echo with a spectrum analyzer.

When plotted, the distance-amplitude response shows graphically the variation of ultrasonic intensity with distance along the transducer axis. It is produced by plotting the return echo amplitude versus the transducer-reflector distance.

The transducer beam profile describes the directivity of the ultrasonic beam. It is obtained by plotting the return echo amplitude from a symmetrical reflector versus the transverse distance from the transducer axis.

The loop sensitivity, indicative of the efficiency of the transducer in converting an electrical signal into an ultrasonic signal and vice versa, is the ratio of the return echo amplitude to the initial electrical impulse.

The electrical noise inherent in a transducer determines the lower limit for detecting a return echo. It was measured with a sensitive oscilloscope.

The Final Test Plan, developed by the SwRI Project Manager and approved by the SAALC Project Engineer, is included in Appendix B.

B. Selection of Transducers

A sample set of 23 transducers was provided by SA-ALC for evaluation. All were longitudinal transducers procured from several commercial sources. Three nominal frequencies - 2.25, 5.0, and 10 MHz - were represented. Several piezoelectric crystal sizes comprised this group: 0.1875-in. (4.76mm), 0.25-in. (6.35mm), 0.312-in. (7.94mm), and 0.375-in. (9.52mm) in diameter. Most had metallic cylindrical cases, but three had square metallic cases and one had a cylindrical plastic case. Table I lists the nominal characteristics of this set of transducers, with an assigned identification number for evaluation purposes.

C. Experimental Method

The characterization measurements were made in an Automation Industries Model US-710 manual-scan water immersion tank using a 0.25-in. (6.35mm) diameter spherical reflector. An Automation Industries Model S80 Pulser-Receiver was used to power the transducer and a Hewlett-Packard Model 140-T Spectrum Analyzer to display the power spectrum. Power spectra and RF waveforms were recorded on Polaroid® photographs. The beam profiles were plotted on a Houston Instruments Model 6452A X-Y Recorder. The distance-amplitude response was obtained by plotting deflection readings from the pulser-receiver oscilloscope versus micrometer readings of distance on the water tank scanning device.

Flaw response was also determined with the transducers and the test standards immersed in water. Special fixturing was built to insure proper alignment of the transducer and specimen, as shown in Figure 2. This alignment was adjusted for each transducer to produce the maximum flaw response. Flaw response patterns were then profiled by measuring the transverse motion necessary to give a 6 dB signal decrease. A Sperry Model UM-721 with a 10N Pulser-Receiver was used to power the transducer. The initial pulse amplitude was also measured and used to normalize the flaw echo amplitude. A water path length of 0.5-in. (12.7mm) was maintained between transducer and standard for each measurement. The metal path length varied with flaw type from 0.5-in. (12.7mm) for the flat-bottom hole specimen to 2-in. (50.8mm) for the other flaw specimens. The loop sensitivity for return echo off a flat surface was also measured. Electrical noise of each transducer was measured with a Tektronix Model 5440 Oscilloscope and recorded on a Polaroid® photograph. A reference electrical noise measurement was made using a dummy load across the pulser-receiver.

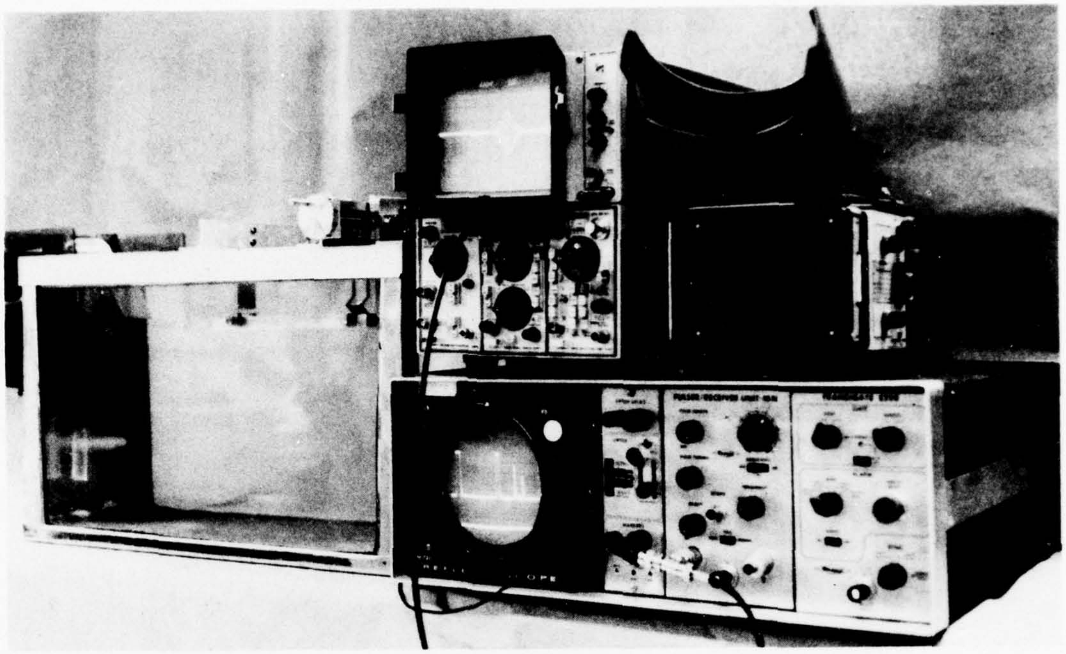
TABLE I

Identification, Frequency, and Size of Test Transducers

Identifying Number	Nominal Frequency	Piezoelectric Crystal Diameter Inches(mm)
A-1	2.25 MHz	0.312(7.94)
A-2	2.25 MHz	0.375(9.52)
A-3	2.25 MHz	0.312(7.94)
A-4**	2.25 MHz	0.375(9.52)
A-5	2.25 MHz	0.25(6.35)
A-6*	2.25 MHz	0.25(6.35)
A-7	2.25 MHz	0.312(7.94)
B-1	5.0 MHz	0.25(6.35)
B-2*	5.0 MHz	0.25(6.35)
B-3	5.0 MHz	0.25(6.35)
B-4	5.0 MHz	0.188(4.76)
B-5	5.0 MHz	0.25(6.35)
B-6	5.0 MHz	0.25(6.35)
B-7	5.0 MHz	0.188(4.76)
C-1	10 MHz	0.25(6.35)
C-2	10 MHz	0.312(7.94)
C-3	10 MHz	0.188(4.76)
C-4	10 MHz	0.25(6.35)
C-5*	10 MHz	0.25(6.35)
C-6	10 MHz	0.312(7.94)
C-7	10 MHz	0.25(6.35)
C-8	10 MHz	0.25(6.35)
C-9	10 MHz	0.188(4.76)

* Square Metallic Housing

** Cylindrical Plastic Housing



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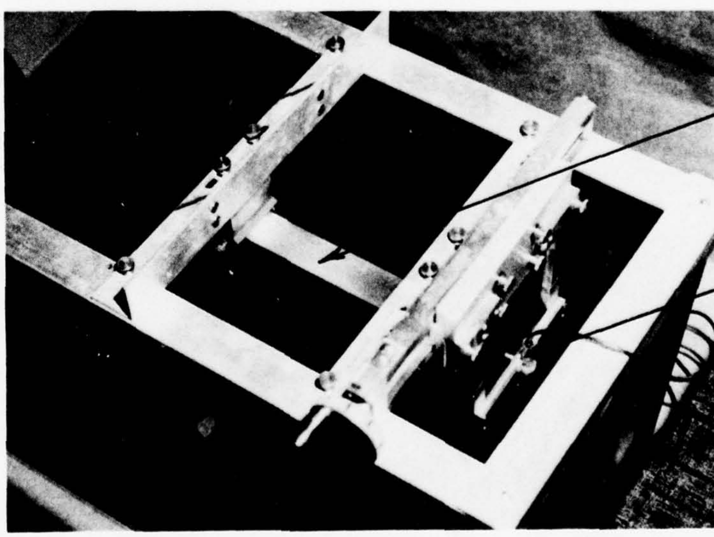
a. Water Immersion Tank and Test Equipment



b. Closeup of Manual Scanning Mechanism with Transducer and Flaw Standard Mounted

FIGURE 2. PHOTOGRAPH OF EXPERIMENTAL APPARATUS

D. Test Results

The data obtained from the experimental measurements were recorded in several forms. Graphs were used to display the beam profile and distance-amplitude information. Polaroid® photographs were used to record the RF power spectrum, RF waveform, and electrical noise. The other measurements were recorded in tabular form. Examples of typical data obtained are discussed below.

1. Electrical and Ultrasonic Characterization

The beam profiles for each transducer were recorded at four transducer-to-reflector distances according to the following scheme: far field maximum point, near field minimum point, and the two -6 dB points on either side of the far field maximum. A typical set of these curves is shown in Figure 3.

The distance-amplitude plot was generated by measuring the echo amplitude in 1/8-in. (3.2mm) steps of the transducer reflector distance. A typical plot of these data is shown in Figure 4.

Spectral information was obtained by recording the RF power spectrum and waveform on Polaroid® phtographs. An example set of these photographs is shown in Figure 5.

2. Flaw Detection

The majority of the transducer performance characteristics considered meaningful in flaw detection were measured on a calibrated Tektronix Model 5440 Oscilloscope and recorded in tabular form. The electrical noise (which determines the limit of sensitivity) was recorded on Polaroid® photographs of oscilloscope displays. Figure 6 shows the electrical noise produced by the pulser-receiver driving (a) a dummy load, (b) a "quiet" transducer, and (c) a "noisy" transducer. The initial electrical pulse amplitude and return echo amplitude from each of the four types of flaws are recorded in Table II, together with the echo amplitude from a flat surface used to calculate the loop sensitivity. The path length in water in each case was 0.5-in. (12.7mm), however, the path length in metal varied and is given in Table II for each specimen.

The flaw response patterns exhibited by all transducers were similar to the far field beam profile pattern shown in Figure 3d. A flaw response pattern for one of the transducers is shown in Figure 7. Since the shape of the far field flaw echo patterns was roughly the same for all transducers, it was only necessary to measure the width at the -6 dB amplitude points (half of maximum amplitude) to characterize each echo response. Table III lists the width at -6 dB response for each type of flaw and for each transducer.

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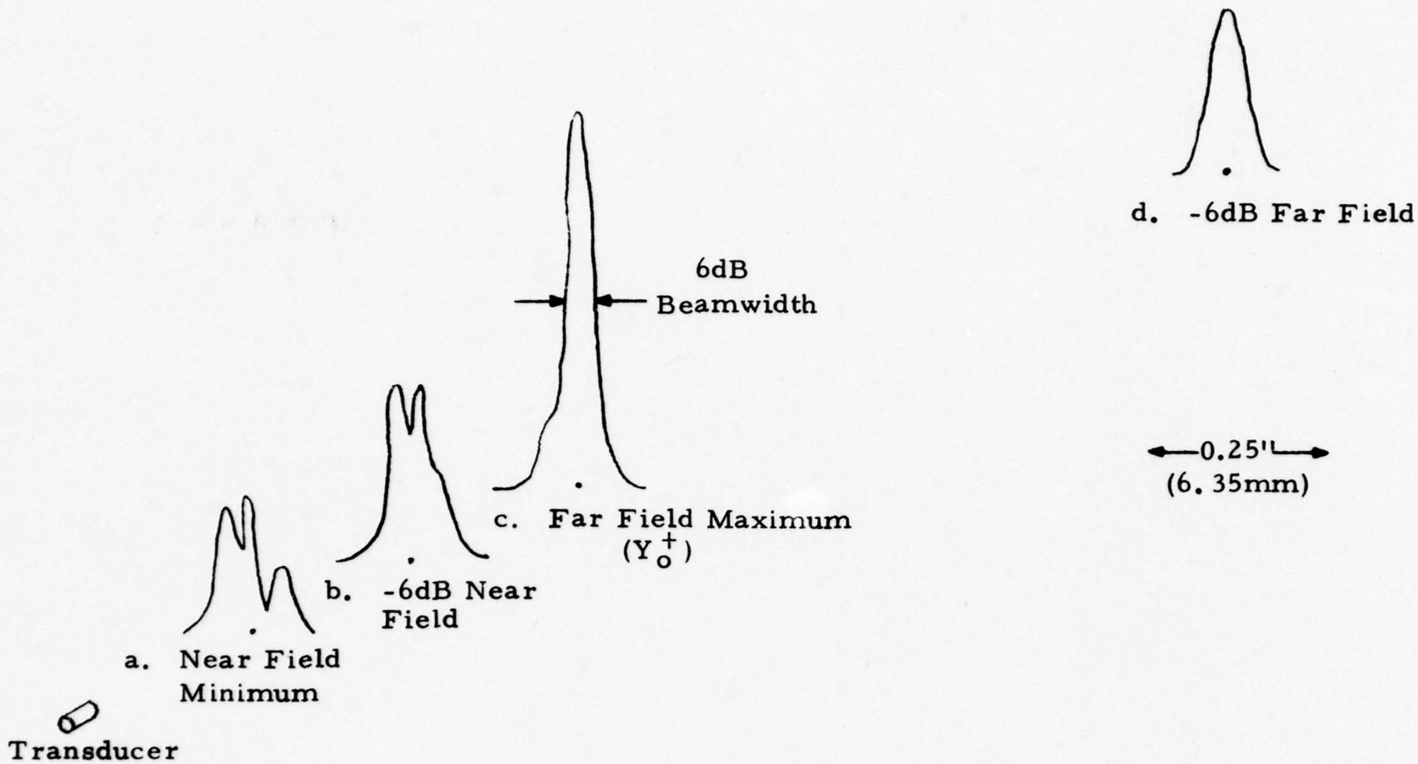


FIGURE 3. BEAM PROFILES OF A 0.25-INCH (6.35mm) SPERICAL REFLECTOR (Typical)

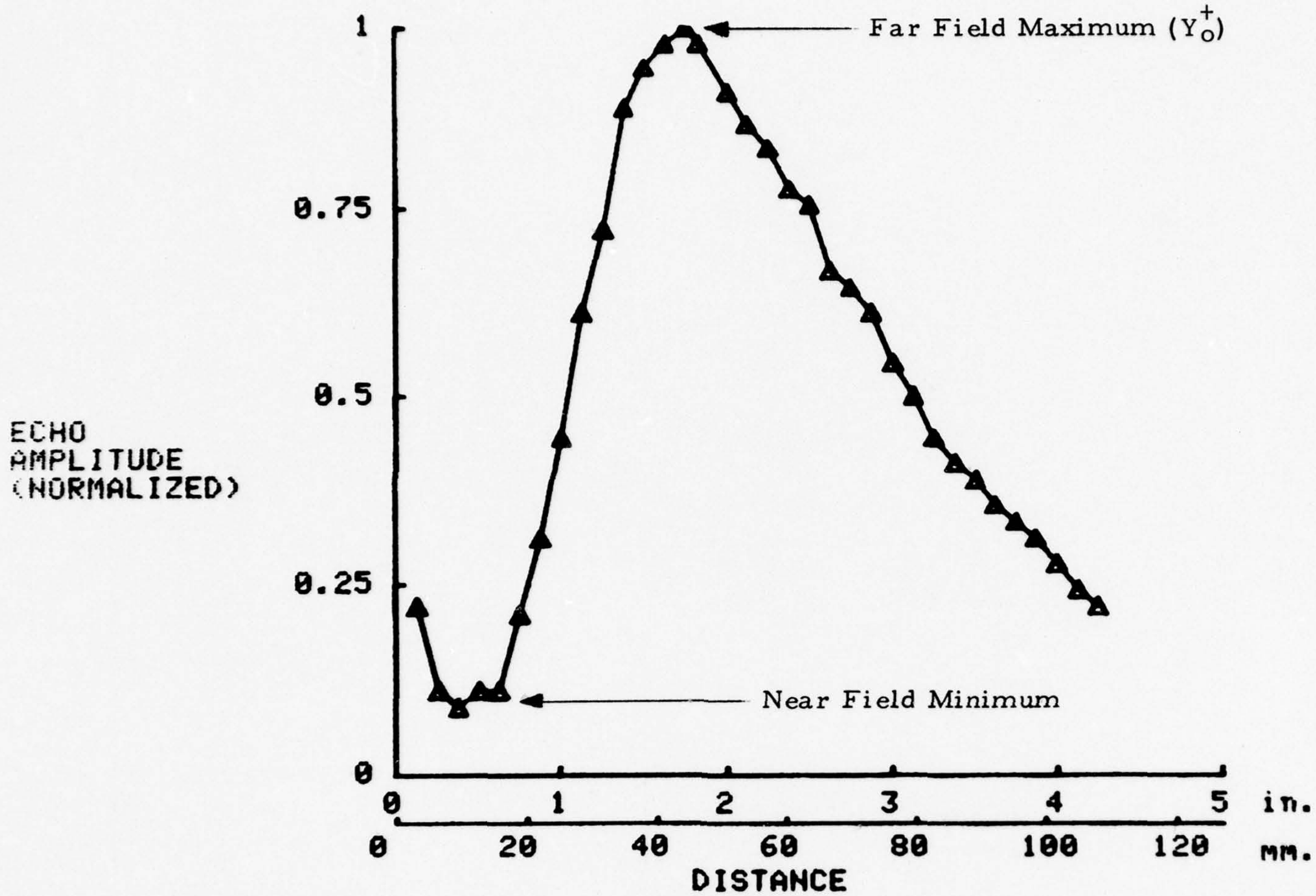
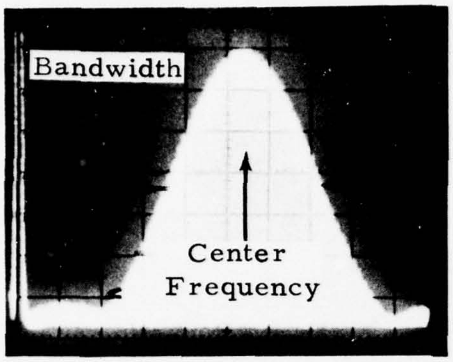
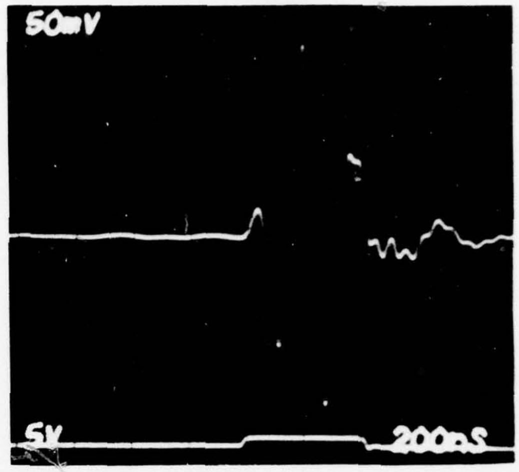


FIGURE 4. DISTANCE AMPLITUDE PLOT (Typical)



Spectrum



RF Waveform

a. Good Spectrum

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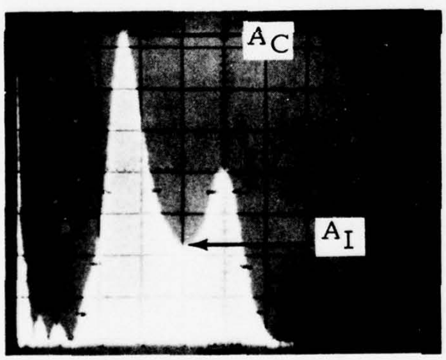
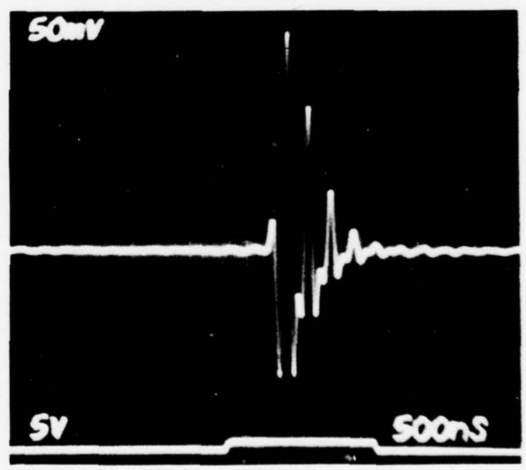
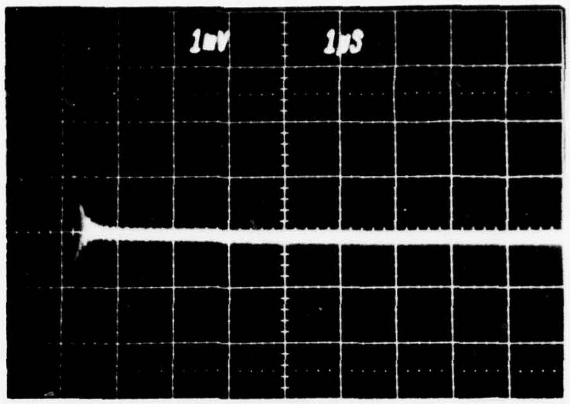




b. Poor Spectrum

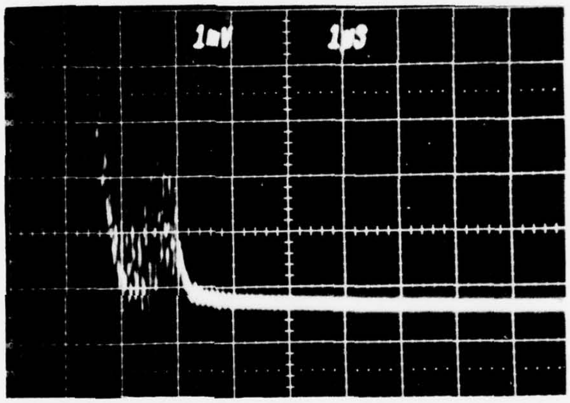
FIGURE 5. RF POWER SPECTRUM AND WAVEFORM SHOWING A GOOD AND POOR SPECTRUM



Amplitude

Time

a. Dummy Load



Amplitude

Time

b. Quiet Transducer

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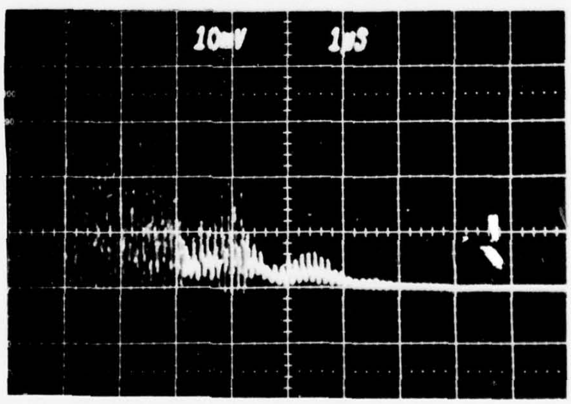

Amplitude

Time

c. Noisy Transducer

FIGURE 6. ELECTRICAL NOISE

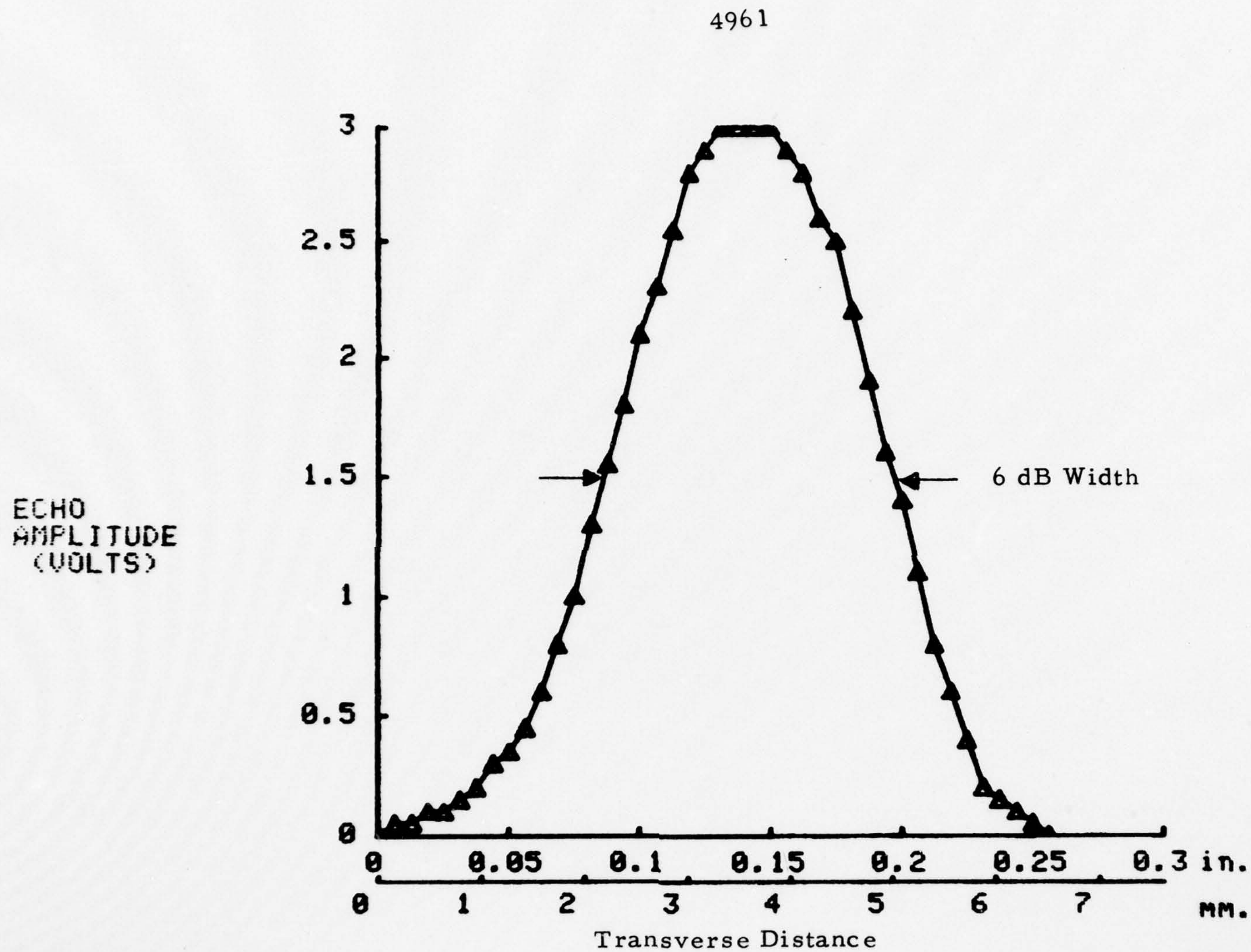

FIGURE 7. FLAW PROFILE (Transducer C6)

TABLE II

Flat Surface and Flaw Response (Echo Amplitude) for Test Transducers

Transducer	Main Pulse (Volts)	Flat Surface Response* (Volts)	Flaw Response (Volts)			
			Flat-Bottom Hole	Elox Notch	Low Cycle Fatigue Crack	High Cycle Fatigue Crack
A-1	720	10	1.49	0.52	0.17	0.15
A-2	800	0.1	0.15	0.22	NE	NE
A-3	1700	1.6	0.24	0.10	NE	NE
A-4	1500	2.8	0.25	0.40	NE	NE
A-5	1400	1.4	0.14	0.11	NE	NE
A-6	1560	0.3	0.09	0.10	NE	NE
A-7	1500	8.4	0.46	0.36	0.10	0.10
B-1	680	5.6	1.21	0.97	0.31	0.12
B-2	1120	1.6	0.72	0.36	0.18	NE
B-3	1680	15.0	1.50	1.15	0.98	0.20
B-4	1050	7.9	0.44	1.22	0.25	0.13
B-5	700	7.6	1.36	1.25	0.46	0.18
B-6	1000	17.0	2.46	1.06	0.30	0.24
B-7	1230	2.8	0.23	0.35	0.15	0.13
C-1	2200	21	6.30	9.10	2.85	1.66
C-2	1900	10	1.34	0.96	1.01	0.17
C-3	2200	0.26	NE	NE	NE	NE
C-4	2100	6.4	0.40	0.22	0.81	0.16
C-5	2050	1.1	0.21	0.16	NE	NE
C-6	1800	10	0.61	0.68	0.57	0.21
C-7	2100	20	0.20	1.80	0.46	0.24
C-8	1800	4.2	1.37	0.69	0.65	0.22
C-9	2000	20	2.21	0.69	1.67	0.56
Path Length in Aluminum Inches (mm)		1.25(31.8)	0.5(12.7)	2.00(50.8)	2.00(50.8)	2.00(50.8)

*used to calculate loop sensitivity
NE - No Detectable Return Echo

Nominal Center Frequency: A = 2.25 MHz, B = 5 MHz, C = 10 MHz

TABLE III

Indicated Flaw Length from -6dB Points, Test Transducers

Transducer	Flat-Bottom Hole	Elox Notch	Low-Cycle Fatigue Crack	High-Cycle Fatigue Crack
A-1	0.385	0.525	*	*
A-2	0.45	0.500	NE	NE
A-3	NE	NE	NE	NE
A-4	0.26	0.55	NE	NE
A-5	0.335	0.58	NE	NE
A-6	0.300	0.475	NE	NE
A-7	0.285	*	*	*
B-1	0.125	0.29	0.25	0.3
B-2	0.180	0.325	0.255	NE
B-3	0.170	0.275	0.235	0.280
B-4	0.145	*	0.205	0.175
B-5	*	0.295	0.25	0.300
B-6	*	*	*	*
B-7	0.250	*	0.25	0.285
C-1	0.112	0.21	0.15	0.212
C-2	0.100	0.22	0.207	0.210
C-3	NE	NE	NE	NE
C-4	0.135	0.225	0.235	0.275
C-5	0.16	0.2	NE	NE
C-6	0.11	0.215	0.185	0.235
C-7	0.1	*	0.21	0.185
C-8	0.11	*	0.15	0.21
C-9	0.13	*	0.15	0.185
Measured Principal Dimension+	0.078	0.125	0.170	0.125

* - No Measurement

NE - No Detectable Return Echo

Nominal Center Frequency: A = 2.25 MHz, B = 5 MHz, C = 10 MHz

+ See Appendix A for detailed information on flaw standard dimensions.

E. Analysis of Test Results

As pointed out in the Introduction, there are no obvious simple measurements which can be easily used to identify transducer performance variation. Thus, a parametric study was undertaken to examine as wide a range of variables as practicable and to determine the significance and dependence of pairwise combinations of the variables through statistical variation and correlation analyses.

1. Calculation of Characterization Parameters

Seventeen characterization parameters were defined and values were computed for each transducer from measured data such as that presented in Section D. The seventeen parameters are given below in five groups and their definitions are detailed in Appendix D.

a. The six parameters defined to describe the characteristics of the RF power spectrum and RF waveform are:

(1) Center Frequency (CF)
(2) Center Frequency Error (CFE)
(3) Bandwidth Ratio (BWR)
(4) Spectrum Symmetry Ratio (SSR)
(5) Spectrum Inflection Ratio (SIR)
(6) Damping (DMP)

Values of these spectrum parameters for the test set of transducers are given in Table IV.

b. The five parameters defined to describe the geometric characteristics of the ultrasonic beam produced by each transducer are:

(1) Far Field Ratio (FFR)
(2) Beamwidth Error (BWE)
(3) Effective Diameter Ratio (EDR)
(4) Beam Symmetry Ratio (BSR)
(5) Beam Inflection Ratio (BIR)

Beam parameters for each of the transducers are given in Table V.

c. The parameter defined to indicate the conversion efficiency of each transducer is loop sensitivity ratio (LSR), and the values of this parameter for each of the transducers are given in Table VI.

TABLE IV

Values of Spectral Performance Parameters (Measured)

Transducer	Center Frequency	Center Frequency Error	Bandwidth Ratio	Spectral Symmetry Ratio	Spectral Inflection Ratio	Damping
A-1	2.61	0.16	0.58	0.1	0.04	5
A-2	2.79	0.24	0.43	0.67	0.46	13
A-3	3.31	0.47	0.55	0.04	0.04	12
A-4	2.79	0.24	0.75	0.06	0.05	9
A-5	3.20	0.42	0.38	0.13	0.13	14
A-6	2.99	0.33	0.37	0.07	0.08	14
A-7	2.30	0.02	0.52	0.04	0.05	8
B-1	5.6	0.12	0.45	0.58	0.28	5
B-2	5.5	0.1	0.33	0.57	0.27	9
B-3	5.5	0.1	0.60	0.03	0.11	5
B-4	5.5	0.1	0.80	0.05	0.05	3
B-5	5.4	0.08	0.46	0.78	0.33	5
B-6	5.4	0.08	0.72	0.01	0.08	3
B-7	5.4	0.08	0.50	0.05	0.10	4
C-1	10.9	0.09	0.31	0.01	0.10	9
C-2	7.7	0.23	0.52	0.15	0	4
C-3	10.3	0.03	0.87	0.19	0.32	4
C-4	6.0	0.40	0.92	0.30	0.04	3
C-5	6.6	0.34	0.64	0.05	0.52	3
C-6	8.5	0.15	0.68	0.10	0	4
C-7	8.5	0.15	0.66	0.18	0	5
C-8	10.5	0.05	0.78	0.01	0	12
C-9	7.1	0.29	1.35	0.09	0	5
Avg.		0.19	0.61	0.19	0.13	7
Std. Dev.		0.13	0.24	0.23	0.15	4
99% Confidence Interval		0.04→ 0.34	0.31→ 0.91	0→0.48	0→0.32	2→ 12

Nominal Center Frequency: A = 2.25 MHz, B = 5 MHz, C = 10 MHz

TABLE V

Values of Beam Parameters (Measured)

Transducer	Far Field Ratio	Beamwidth Error	Effective Diameter Ratio	Beam Symmetry Ratio	Beam Inflection Ratio
A-1	0.47	0.57	0.67	0.16	0.12
A-2	0.75	0.11	1.13	0.03	0.00
A-3	0.55	0.42	0.67	0.08	0.00
A-4	0.45	0.85	0.60	0.02	0.00
A-5	0.74	0.19	0.75	0.03	0.00
A-6	0.47	0.23	0.88	0.04	0.00
A-7	0.40	0.64	0.96	0.12	0.00
B-1	0.59	0.03	0.94	0.10	0.00
B-2	0.43	0.17	1.12	0.09	0.00
B-3	0.60	0.37	0.93	0.17	0.06
B-4	0.77	0.36	0.79	0.04	0.00
B-5	0.61	0.18	2.13	0.15	0.00
B-6	0.79	-0.38	1.61	0.09	0.00
B-7	0.62	0.94	0.72	0.12	0.00
C-1	0.39	1.48	0.48	0.26	0.00
C-2	0.47	0.88	0.98	0.28	0.01
C-3	0.82	-0.16	1.74	0.50	0.30
C-4	0.95	0.46	1.27	0.14	0.00
C-5	0.50	1.20	0.95	0.52	0.26
C-6	0.46	1.71	0.73	0.06	0.00
C-7	0.94	0.72	0.95	0.02	0.00
C-8	0.63	2.11	0.61	0.12	0.00
C-9	1.07	1.26	0.58	0.04	0.00
Avg.	0.63	0.62	0.96	0.14	0.03
Std. Dev.	0.19	0.60	0.40	0.13	0.08
99% Confidence Interval	0.39→0.87	-0.13→1.37	0.46→1.46	0→0.32	0→0.13

Nominal Center Frequency: A = 2.25 MHz, B = 5 MHz, C = 10 MHz

TABLE VI

Noise Ratio, Loop Sensitivity, and Flaw Response Ratio Values (Measured)

Transducer	Noise Ratio @ 2μs	Noise Ratio @ 10μs	Loop Sensitivity Ratio (dB)	Flaw Response Ratio (dB)			
				Flat-Bottom Hole	Elox Notch	Low-Cycle Fatigue Crack	High-Cycle Fatigue Crack
A-1	9	13	-37	-54	-63	-73	-74
A-2	9	7	-78	-75	-71	NE	NE
A-3	7	3	-61	-77	-65	NE	NE
A-4	6	2	-55	-76	-72	NE	NE
A-5	4	1	-60	-80	-82	NE	NE
A-6	6	1	-74	-85	-84	NE	NE
A-7	8	15	-45	-70	-72	-84	-84
B-1	73	2	-42	-55	-57	-67	-75
B-2	77	2	-57	-64	-70	-79	NE
B-3	21	3	-41	-61	-63	-65	-79
B-4	15	1	-43	-68	-53	-73	-78
B-5	96	2	-39	-54	-55	-64	-72
B-6	70	2	-35	-52	-60	-71	-72
B-7	65	2	-53	-75	-71	-78	-80
C-1	201	5	-40	-51	-48	-58	-62
C-2	95	2	-46	-63	-66	-66	-81
C-3	10	0	-79	NE	NE	NE	NE
C-4	34	2	-50	-74	-80	-68	-82
C-5	9	0	-65	-80	-82	NE	NE
C-6	8	0	-45	-69	-69	-70	-79
C-7	7	0	-40	-80	-61	-73	-79
C-8	162	6	-53	-62	-68	-69	-78
C-9	20	0	-40	-59	-69	-62	-71
Avg.	44	3	-51	-69	-69	-79	-85
Std. Dev.	65	4	13	12	11	15	12
99% Confidence Interval	0→126	0→8	-66→-36	-84→-54	-82→-56	-98→-60	-100→-70

NE - No Detectable Return Echo Nominal Center Frequency: A=2.25 MHz, B=5 MHz, C=10 MHz

d. The parameter defined to describe the electrical noise characteristics of each transducer is the noise ratio (NR). Because this parameter is time dependent, values of the parameter were computed for each transducer at 2 and 10 microseconds after the leading edge of the main pulse. These values are also given in Table VI.

e. The parameter defined to describe the response of each transducer to each of the four flaw standards is the flaw response ratio (FRR). The values of this parameter computed for the response of each of the transducers for each of the standard flaws are given in Table VI.

2. Variability of Characterization Parameters

Variability of the characterization parameters was analyzed by calculating the average, the standard deviation, and the 99% confidence interval for each of the parameters. The 99% confidence interval represents the variability range for each parameter which would be expected if all Air Force ultrasonic transducers were characterized, assuming that the present lot is representative. The results of this statistical analysis on the values of each of the parameters for the transducers are given in Tables IV, V, and VI.

Statistical analysis shows the extreme variability which can be expected in the performance characteristics of a typical transducer. For example, the beamwidth error averages 0.62, i.e., the average ultrasonic beam is 62% wider than it should be. The 99% confidence interval indicates that the ultrasonic beamwidth of a set of identical transducers could be expected to vary from 87% to 237% of the theoretically calculated value. This is a possible variation of a factor of almost four in the beamwidth.

3. Correlation of Characterization Parameters

In order to identify any dependence between the characterization parameters, the correlation coefficients between every pair of parameters were calculated. Because of the limited scope of the present program only the zero-order, linear correlation coefficients were computed.

The correlation coefficients between pairs of parameters were calculated using a BASIC computer program on a Tektronix 4051 Graphics System minicomputer. This program is included in Appendix C. The results of this analysis are summarized below. In this discussion, a correlation coefficient value of zero indicates no relationship between the pair of parameters, while a value of ± 1 indicates perfect correspondence. A positive coefficient simply means that the parameters are directly related, whereas a negative coefficient indicates an inverse relationship.

There is a twofold purpose in the calculation of these correlation coefficients. First, if some of the characteristics are highly dependent on each other, then the measurement of only one of the interdependent parameters may be sufficient. Thus, high correlations between the characteristic parameters may allow reduction of the number of measurements needed to characterize each transducer. The second purpose is to identify any relationship between the flaw response of a transducer and other characteristic parameters. The characteristic parameters which are shown to be related to the flaw response of a transducer can then be used to establish procurement and certification criteria.

a. Correlation Among Characterization Parameters

Table VII contains the correlation coefficients between pairs of the twelve parameters calculated from the electrical and ultrasonic beam measurements described in previous sections of this report. There are only four pairs of parameters which show correlation greater than 50%:

(1) the spectrum symmetry ratio (SSR) and spectrum inflection ratio (SIR)
(2) the bandwidth ratio (BWR) and the far field ratio (FFR)
(3) the beamwidth error (BWE) and the effective diameter ratio (EDR)
(4) the beam symmetry ratio (BSR) and the beam inflection ratio (BIR)

The correlation between the symmetry and the inflection ratios is understandable, since an inflection point implies asymmetry. Also, since the beamwidth is used in calculating both beamwidth error and effective diameter ratio, the correlation of these factors is obvious. The only surprise is the correlation between the bandwidth and the far field maximum distance.

b. Correlation with Flaw Detection Response

To reduce confusion in reporting the large number of parameters investigated, the correlations of transducer characteristics with the flaw detection response are divided into three logical areas: first, the correlations among the flaw response ratios (FRR) of the various flaws is analyzed; next, the correlation between the FRR of each transducer and the spectral parameters is examined; and finally, the correlation between the FRR's and the beam parameters is analyzed.

TABLE VII

Correlation Coefficients for Twelve RF and Ultrasonic Parameters

	CFE	BWR	SSR	SIR	DMP	FFR	BWE	EDR	BSR	BIR	LS
CF	-0.37	0.28	-0.14	-0.07	-0.33	0.19	-0.21	-0.17	0.45	0.24	0.14
CFE		0.07	-0.08	-0.02	0.34	0.16	0.04	-0.01	-0.13	-0.06	-0.35
BWR			-0.29	-0.30	-0.44	0.67	0.10	0.05	0.03	0.18	0.17
SSR				0.59	0.05	0.08	0.44	0.27	-0.11	-0.13	-0.13
SIR					0.01	-0.07	0.41	0.21	0.48	0.51	-0.50
DMP						-0.25	-0.44	-0.25	-0.38	-0.32	-0.50
FER							-0.21	0.28	-0.16	0.00	0.02
BWE								0.68	0.06	-0.09	0.19
EDR									-0.03	0.02	-0.25
BSR										0.86	-0.40
BIR											-0.30

CF = Center Frequency
CFE = Center Frequency Error
BWR = Bandwidth Ratio
SSR = Spectrum Symmetry Ratio
SIR = Spectrum Inflection Ratio
DMP = Damping
FFR = Far Field Ratio
BWE = Beamwidth Error
EDR = Effective Diameter Ratio
BSR = Beam Symmetry Ratio
BIR = Beam Inflection Ratio
LS = Loop Sensitivity

(1) Correlation Among Flaw Response Ratios for Different Flaw Types

The correlations between flaw response for the specific flaw types are given in Table VIII. It was found that these correlations could be improved by correcting for size and frequency variations among the transducers. This correction is based on the fact that the flaw echo amplitude is affected by the ultrasonic wavelength and by the transducer radiating area. The dependence on radiating area is the result of power considerations, in both the initial ultrasonic pulse and the received electrical echo. Correction for this effect was applied by multiplying the FRR value by the ratio of the frequency to the square of the radiating area. The numbers in parentheses are the correlation coefficients obtained before applying these correction factors. As could be expected, the correlation between FRR values for the different flaw types is high, but not perfect. Thus, there is a correspondence between the response to different types of flaws, although the nature of this correspondence is not simple.

TABLE VIII

Correlation Among Flaw Response Ratio (FRR) Values for Various Flaw Specimens, All Transducers

	Elox Notch	Low-Cycle Fatigue Crack	High-Cycle Fatigue Crack
Flat-Bottom Hole	0.93(0.82)*	0.92(0.78)	0.92(0.76)
Elox Notch		0.88(0.68)	0.91(0.71)
Low-Cycle Fatigue Crack			0.97(0.92)

* Values in parentheses are those before applying correction for transducer frequency and size.

(2) Correlation Among Flaw Response Ratio (FRR) Value and Spectral Parameters

The correlation coefficients between the FRR values and the spectral parameters were calculated using the computer program given in Appendix C. Correlations among these parameters were also improved by correcting the FRR values for frequency and size variations in the transducers. Table IX lists the correlation coefficients. There is little indication of correlation between any of the spectral parameters and

TABLE IX

Correlation of Spectral Parameters with Flaw Response Ratio Values

	Center Frequency	Center Frequency Error	Bandwidth Ratio	Spectrum Symmetry Ratio	Spectrum Inflection Ratio	Damping
Flat-Bottom Hole	0.45(0.05)	-0.34(-0.33)	0.04(-0.08)	-0.22(0.14)	-0.35(-0.19)	-0.06(-0.20)
Elox Notch	0.44(0.06)	-0.31(-0.31)	-0.02(-0.19)	-0.24(0.10)	-0.38(-0.26)	-0.03(-0.16)
Low-Cycle Fatigue Crack	0.64(0.46)	-0.40(-0.45)	0.20(0.19)	-0.22(0.05)	-0.44(-0.39)	-0.27(-0.50)
High-Cycle Fatigue Crack	0.60(0.39)	-0.40(-0.48)	0.19(0.19)	-0.33(-0.09)	-0.44(-0.40)	-0.22(-0.49)
Average	0.53(0.24)	-0.36(-0.39)	0.10(0.03)	-0.25(0.05)	-0.40(-0.31)	-0.14(-0.34)
Std. Dev.	0.10(0.22)	0.04(0.08)	0.11(0.19)	0.05(0.10)	0.04(0.10)	0.12(0.18)
99% Conf. Range	0.38(0.82)	0.15(0.30)	0.41(0.71)	0.19(0.38)	0.15(0.38)	0.45(0.68)
Corr. Rating	Some(None)	Some(Some)	None(None)	Some(None)	Some(Some)	None(None)

* Values in Parentheses are before correction for transducer size and frequency.

the flaw response ratio (FRR) values. The final line in the table gives a correlation rating for each parameter varying from "none" to "some". This rating is based on a statistical analysis of the variance of the correlation coefficient for the four FRR values. A numerical correlation rating is calculated from the following formula

$$CR = |A| - CL/2$$

where A is the average and CL is the 99% confidence range. The qualitative rating is derived from the following

None	$CR < 0.0$
Slight	$0.0 \leq CR \leq 0.1$
Some	$0.1 \leq CR \leq 0.5$
Good	$0.5 \leq CR \leq 0.9$
Excellent	$0.9 \leq CR \leq 1.0$

It is obvious from Table IX that the "best" correlation is with the true center frequency of the transducer. Less pronounced correlation is noted with the center frequency error, the spectral symmetry, and the spectrum inflection parameters. This analysis would indicate no correlation with the bandwidth or damping of the transducer.

(3) Correlation Between Flaw Response Ratio (FRR) and Beam Parameters and Loop Sensitivity

The correlation coefficients between the FRR values and the beam parameters and loop sensitivity are given in Table X. These FRR values were also corrected for variations in transducer size and frequency. The correlation rating scheme developed in Section III. E. 3. b. was used to rate the correlations between the flaw response ratios and the beam parameters. The best beam parameter correlations were with beamwidth error and effective radiating area. A secondary correlation is observed with the beam inflection. There is no apparent correlation with beam symmetry or far field ratio. The loop sensitivity has the highest correlation to flaw response of any of the characteristic parameters, with an average of 93% correlation after correction for transducer size and frequency.

TABLE X

Correlation of Beam Parameters with Flaw Response Ratio Values

	Effective Radiating Area	Beamwidth Error	Beam Symmetry Ratio	Beam Inflection Ratio	Far Field Ratio	Loop Sensitivity
Flat-Bottom Hole	-0.53(0.12)	0.66(0.15)	-0.11(-0.22)	-0.32(-0.44)	-0.18(-0.18)	0.92(0.79)
Elox Notch	-0.61(-0.04)	0.63(0.14)	-0.18(-0.37)	-0.37(-0.56)	-0.15(-0.15)	0.91(0.76)
Low-Cycle Fatigue Crack	-0.50(0.00)	0.65(0.29)	-0.04(-0.10)	-0.27(-0.36)	0.02(0.12)	0.94(0.84)
High-Cycle Fatigue Crack	-0.55(-0.01)	0.68(0.30)	-0.03(-0.10)	-0.22(-0.31)	0.01(0.13)	0.95(0.86)
Average	-0.55(0.02)	0.66(0.22)	-0.09(-0.20)	-0.30(-0.42)	-0.08(-0.02)	0.93(0.81)
Std. Dev.	0.05(0.07)	0.02(0.09)	0.07(0.13)	0.06(0.11)	0.11(0.17)	0.02(0.05)
99% Confidence Range	0.19(0.26)	0.07(0.34)	0.26(0.49)	0.22(0.41)	0.38(0.64)	0.07(0.19)
Corr. Rating	Some(None)	Good(Slight)	None(Slight)	Some(Some)	None(None)	Excellent(Good)

* Values in parentheses are before correction for transducer size and frequency.

F. Discussion of Results

1. Transducer Variability

In agreement with previously reported work, [1,2] the performance of transducers examined in this program showed a wide range of variability. For most of the transducers evaluated, the frequency and crystal size were not the same values specified on the nameplate. Variation in the characteristic parameters was analyzed by calculating the average, standard deviation, and a 99% confidence interval for each parameter.

a. Spectrum Parameters

An analysis of the parameters involving the RF spectrum in Table IV shows the high variability among the test transducers. The average center frequency error is 19%. The 99% confidence interval shows that most transducers will be at least 4% off in frequency. The average spectrum symmetry ratio is 0.19, and the average spectrum inflection ratio is 0.13.

b. Beam Parameters

The analysis of the beam parameters in Table V shows several interesting results. The far field ratio averages only 0.63, with the 99% confidence interval reaching only 0.87. The beam-width error averages 62%, with a 99% interval from -13% to 137%. Thus, on average, the beam is significantly wider than expected. The effective diameter ratio averages 96%, but the 99% interval is from 0.46 to 1.46. The beam symmetry and inflection have smaller averages with 99% intervals up to 30% and 13%, respectively.

c. Other Parameters

The loop sensitivity ratio in Table VI for the test transducers, showed variability of an almost unbelievable amount. The 99% confidence range of 32 dB represents a response variation of a factor of 45, and the variation in the flaw response ratio values was of similar magnitude. Seven of the twenty-three transducers produced no discernible flaw echo from the fatigue cracks. The remaining transducers showed variation of as much as a factor 40 over the 99% confidence band.

2. Correlation Analysis

Correlation analysis was performed to identify and possibly eliminate redundant characterization measurements and thereby develop a means of predicting transducer performance based on a minimum number of independent measurements. First, the correlations between the characterization parameters were computed with the aim of eliminating any of the dependent measurements. A moderate reduction in the number of measurements appears possible from this analysis inasmuch as significant correlation was obtained with the following four pairs of parameters:

(a) Beam Inflection and Beam Symmetry
(b) Beamwidth and Effective Diameter
(c) Bandwidth and Far Field Distance
(d) Spectrum Inflection and Spectrum Symmetry

Correlation analysis was also performed in an attempt to define the sources of the extreme variability in transducer performance. Because of the complexity and interdependence of the transducer characteristics, only one correlation was found with a high degree of certainty: the correlation between the flaw response ratio (FRR) and the loop sensitivity. This correlation was even apparent before applying corrections for transducer size and frequency variations. The average correlation between the loop sensitivity and the response of the transducer to the test flaws of all types was 0.81 before, and 0.93 after correction for size and frequency.

Correlation of flaw response to actual center frequency had an average correlation coefficient of 0.52, which indicates the well known fact that the ability to detect small flaws such as fatigue cracks increases with increasing frequency.

Correlation of flaw response to beamwidth error had an average correlation coefficient of 0.66. Notice that this is a positive correlation, indicating that the larger the beamwidth error the better the transducer. This may appear somewhat surprising, but examination of the error values in Table V make clear that this correlation simply shows that negative values of beamwidth error (beam too narrow) indicates poor performance.

There were several secondary correlations of flaw response to other parameters. These are, in descending order: effective radiating area (-0.55), spectrum inflection ratio (-0.43), center frequency error (-0.36), beam inflection ratio (-0.30), and spectrum

symmetry ratio (-0.28). Because of dependence on more highly correlated parameters, the effective radiating area and spectrum symmetry can be eliminated from consideration.

3. Performance Rating

The primary independent correlations of transducer parameters to flaw response as detailed in the previous sections were, in order of correlation, (1) loop sensitivity, (2) beamwidth, (3) center frequency, (4) spectrum inflection, and (5) beam inflection. A "performance rating" for each transducer can be developed, utilizing the weighted sum of five terms, one for each of these correlated parameters. The correlation coefficient for each parameter is used as the weighting factor in this sum.

The performance rating of each parameter is based on the statistical analysis of the variability of that parameter. For example, the rating for the loop sensitivity is defined as the difference (in dB) between the loop sensitivity for a particular transducer and the best loop sensitivity for the set (the upper bound of the 99% confidence band). For ratings of the remaining parameters, the following procedure was used: each of the parameter values defines, for a given transducer, a deviation from the "correct" performance. Thus, the rating is assumed to depend linearly on the value of the parameter. The value of the parameter corresponding to the upper limit of the 99% confidence interval is conveniently assigned a rating value of -5. The beamwidth error rating has a dual value since there are both positive and negative deviations from the correct beamwidth. Thus, a rating is defined for both a positive and negative beamwidth ratio. The defining equations for the performance ratings are given in Appendix D.

The values of the ratings for each transducer characterization parameter are given in Table XI. These values for each parameter are combined into a total rating by a weighted sum. The weight for each parameter is the absolute value of the average correlation of that parameter to the flaw response ratios, given in Tables VIII, IX, and X. These weights are listed in Table XI.

To test the validity of this performance rating, a correlation analysis was performed between the calculated rating and the flaw response ratio for each transducer. The correlation coefficients resulting from this analysis are given in Table XII. The average value of the coefficient is 0.82, which is good correlation by the correlation rating scheme established in Section II.E.2.b.(2).

TABLE XI

Transducer Performance Rating Based on Parameters with Good Flaw Response Correlation

Transducer	Loop Sensitivity Rating	Center Frequency Rating	Beamwidth Rating	Spectrum Inflection Rating	Beam Inflection Rating	Total Rating	Class
A-1	-2	-2	-2	-1	-4	-6	G
A-2	-43	-3	0	-7	0	-45	P
A-3	-26	-7	-2	-1	0	-29	P
A-4	-20	-3	-3	-1	0	-23	P
A-5	-25	-6	-1	-2	0	-28	P
A-6	-39	-5	-1	-1	0	-40	P
A-7	-10	0	-2	-1	0	-11	F
B-1	-7	-2	0	-4	0	-9	F
B-2	-22	-1	-1	-4	0	-23	P
B-3	-6	-1	-1	-2	-2	-9	F
B-4	-8	-1	-1	-1	0	-9	F
B-5	-4	-1	-1	-5	0	-7	G
B-6	0	-1	-13	-1	0	-11	F
B-7	-18	-1	-4	-1	0	-20	P
C-1	-5	-1	-6	-1	0	-10	F
C-2	-11	-3	-3	0	0	-14	F
C-3	-44	0	-5	-5	-10	-50	P
C-4	-15	-6	-2	-1	0	-18	F
C-5	-30	-5	-4	-7	-9	-41	P
C-6	-10	-2	-6	0	0	-15	F
C-7	-11	-2	-3	0	0	-13	F
C-8	-18	-1	-8	0	0	-22	P
C-9	-5	-4	-5	0	0	-10	F
Weight	0.93	0.52	0.66	0.43	0.30		

G = Good F = Fair P = Poor

Nominal Center Frequency: A = 2.25 MHz, B = 5 MHz, C = 10 MHz

TABLE XII

Correlation Between Calculated "Performance Rating" and Flaw Response Ratio, All Transducers

	Flat-Bottom Hole	Elox Notch	Low-Cycle Fatigue Crack	High-Cycle Fatigue Crack
Correlation Coefficient	0.83	0.78	0.83	0.83

Average: 0.82

A preliminary acceptance limit may be established from the performance rating as follows. In the loop sensitivity category the criterion is:

Good $\longrightarrow$ LS Rating $\geq$ -6
Fair $\longrightarrow$ LS Rating $\geq$ -12
Poor $\longrightarrow$ LS Rating $<$ -12.

For all other parameters the limits are established as

Good $\longrightarrow$ Rating $\geq$ -1
Fair $\longrightarrow$ Rating $\geq$ -2
Poor $\longrightarrow$ Rating $<$ -2

The weighted sum of these individual acceptance limits gives the acceptance limit for the total rating as:

Good $\longrightarrow$ Total Rating $\geq$ -7
Fair $\longrightarrow$ Total Rating $\geq$ -18
Poor $\longrightarrow$ Total Rating $<$ -18.

Based on this classification scheme, only two of the 23 transducers are rated as "good" transducers. Eleven transducers would be rated as "fair". The remaining ten transducers would be rated as "poor". Thus, almost half of the supplied lot would be rejected for use in flaw detection.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The conclusions presented in this report must be recognized as somewhat tentative, based on several limitations. First, the sample transducer set consisted of only 23 units, all from only one source, the San Antonio Air Logistics Center. Second, flaw detection performance and other measurements were restricted to longitudinal wave, immersion conditions, and most of the ultrasonic inspection performed in the Air Force utilizes shear waves produced using longitudinal transducers and an appropriate mode conversion wedge. It is certain that mode conversion will not improve the transducer variability, but simply introduce another variable. Nevertheless, several conclusions can be drawn with considerable certainty; others are implied. A recommended course of action can now be charted and specific effort directed toward improvement of flaw detection reliability.

1. Variability of Transducer Performance

It is obvious that wide variation in the performance of transducers used routinely in Air Force UT inspection exists. Seven of the 23 transducers examined were unable to detect the relatively large fatigue cracks used in this investigation. The remaining transducers displayed variation in fatigue crack response by a factor of 40. All but one of the transducers could detect the Elox notch, but with a total response variation amounting to a factor of 20. All but one of the transducers could detect the flat-bottom hole with a response variation of a factor of 30. Using a reasonable system of rating developed in the program and detailed in Section III. F. 3 only two of the 23 transducers are rated "good". Thus, to the extent that the set of 23 transducers evaluated is representative of all Air Force transducers, only slightly more than half (13 out of 23) may be considered acceptable for fatigue crack detection.

2. Flaw Response Correlation

A strong correlation between transducer loop sensitivity and flaw detection performance was demonstrated. Since loop sensitivity can be easily characterized and specified, it appears to provide a preliminary criterion for certification of transducers for service. However, loop sensitivity itself is a complex function of many manufacturing parameters and presents a serious challenge to good control.

3. Transducer Electrical and Ultrasonic Parameters

Transducer flaw response and the 13 electrical and ultrasonic parameters defined in the program yielded only moderate correlation. This indicates that most of these parameters may be significant, but no single factor (such as error in center frequency for example) dominates the response of the transducer to flaws.

4. Transducers with 2.25 MHz Center Frequency

Most of the 2.25 MHz transducers did not produce detectable responses from the relatively large fatigue cracks used in this study. Although most Air Force T.O.'s examined do not specify these low frequency transducers, their poor flaw detection performance in this program highlights the general conclusion that they should not be used to search for small flaws.

5. Prediction of Flaw Response

Accurate flaw response predictions, based on measured transducer parameters, would add a considerable degree of confidence to the reliability of flaw detection. It may be concluded that specification of such parameters and the certification of transducers based on these specifications is a reasonable goal.

B. Recommendations

Results of the program indicate that there is considerable room for improvement in the flaw detection performance of in-service ultrasonic transducers, and that specification of parameters leading to this goal is possible. Several specific steps are indicated in achieving this objective. Recommendations for further effort in this direction are explained below.

1. Reference Transducers

Since all the transducers examined were in-service Air Force units, the statistical analysis carried out in this program had no absolute reference (for example, the ratings would be biased if none of the transducers were truly "good"). It is recommended that a set of high quality, laboratory transducers of known characteristics be acquired as control units, to serve as a baseline reference for performance characterization of other transducers.

2. Shear Wave Mode Operation

All of the measurements reported in this program were made in the longitudinal mode because of the greater control possible. However, it is recognized that the majority of Air Force UT measurements are made in the shear wave mode. The shear wave mode is normally obtained by adding a plastic wedge to a longitudinal transducer. Accordingly, measurements on longitudinal mode transducers provide more fundamental information on inherent characteristics of transducers. Nevertheless, it is recommended that procedures be established, and further testing performed, not only on longitudinal wave transducers but also on shear wave mode transducers.

3. Effect of Flaw Size

Conclusions drawn in this report were based on the measurement of response to four standards, all with acoustic reflectors of approximately the same area. It is recommended that further studies include service-induced flaws with a variety of sizes.

4. Broader Sampling Base

The 23 transducers evaluated in this program all came from the same source, San Antonio Air Logistics Center. It is recommended that further studies include a larger sample, carefully selected from a variety of sources and applications areas.

5. Beam Alignment

One parameter which was not examined in this study was beam alignment. Although not critical in longitudinal wave immersion inspection, for shear wave operation it is critical. Mode conversion depends on proper alignment of the beam with respect to the conversion wedge, and it may be expected that alignment will be indicated as an additional source of variability, whose measurement should be included in a future investigation.

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APPENDIX A

DESCRIPTION OF FLAW STANDARDS

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DESCRIPTION OF FLAW STANDARDS

Table A-I lists the important characteristics of each flaw standard. One of these standards was a #5 flat-bottom hole standard manufactured by Automation Industries (Aluminum reference standard #7075-5-0050, Serial Number 1068). The metal path length to the bottom of the hole is 0.5-in. (12.7mm). The other flaw standards were selected from a set of reference blocks provided by the Air Force. This table also gives the total number of cycles applied to each fatigue crack specimen. A more complete history of fatigue cycling, including the schedule of loading and the crack growth rates, is presented in the report of Reference (3).

The length measurements are the microscopically observed surface lengths. The depth was microscopically measured for the Elox notch specimen, but estimated for the fatigue cracks. (Since the half-penny flaws open on only one surface, by convention their crack depth is defined to be half of the total distance that the flaw extends across the surface.) These estimates were verified based on the growth patterns observed for three fractured specimens, microscopic observations of the surface crack length, and four-contact electric probe measurements. The cross-sectional area of the flaw was estimated from these depths and the lengths. For the Elox notch the width of the gap was measured microscopically.

TABLE A-I

CLASSIFICATION OF FLAW SIZES. The flaw type: FBH = Flat-Bottom Hole, Elox = Electric Discharge Machined Notch, LC = Low Cycle (high stress) Crack, HC = High Cycle (low stress) Crack, the total number of fatigue cycles and the flaw dimensions for the two fatigue crack specimens.

			Flaw Dimensions									
			Diameter		Length		Depth		Area		Gap	
Flaw Type	Flaw Shape	Fatigue Cycles	Inches	(mm)	Inches	(mm)	Inches	(mm)	In^2	(mm^2)	Inches	(mm)
FBH	Cylindrical Hole	0	0.078	(1.981)			0.750	(19.050)	0.005	(3.226)		
Elox	Half-Penny	0			0.250	(6.350)	0.125*	(3.175)	0.024*	(15.484)	0.016	(0.406)
LC	Half-Penny	8,700			0.340	(8.636)	0.170*	(4.318)	0.045*	(29.032)		
HC	Half-Penny	145,000			0.250	(6.350)	0.125*	(3.175)	0.024*	(15.484)		

* Estimated values

APPENDIX B

APPROVED FINAL TEST PLAN

APPROVED FINAL TEST PLAN

A. Task A - Transducer Characterization

1. Perform Spectrum Analysis

For each transducer, the spectrum of an echo from a flat-bottom hole will be analyzed using an HP 140-T spectrum analyzer. Data will be recorded on Polaroid photographs. The center frequency and bandwidth for each transducer will be measured from these photographs.

2. Measure Radiation Patterns

The profile of the beam of each transducer will be measured in water using a spherical reflector. These profiles will be recorded by an X-Y plotter at four points: far field, near field, and two intermediary points. The far field point will be selected by maximizing the echo amplitude. Profiles for several orientations of each transducer will be repeated at least three times to assess reproducibility of the data. For the far field point, at least two different orientations of the transducer will be profiled, i.e., at 9 degrees and 90 degrees. If necessary, as many as twelve profiles may be run, i.e., every 15 degrees. For the other field positions, at least two profiles will be run, i.e., at 0 degrees and 90 degrees.

A distance-amplitude plot will be made for each transducer. This will be done in water using a spherical reflector. The data will be presented as a graph.

3. Classify Transducers

The data collected in this task will be used to classify the transducers with respect to their spectrum and radiation patterns. Analysis of any relationship between spectrum and radiation pattern will be performed.

B. Task B - Transducer Response to Defects

1. Fatigue Crack Standards

The responses of the transducers will be compared in two ways: pattern of response and maximum response. Appropriate

graphs to display the pattern will be made. The maximum response will be characterized by: echo S/N and echo amplitude.

2. Standard Defects

The responses of the transducer to standard defects will also be measured. These defects will be flat-bottom holes. Elox notch specimens will be provided by the Government if required.

3. Classify Transducers

The measurements made in this task will be used to classify the transducers as having good to bad ability to detect defects.

C. Task C - Performance Parameters

The results of Tasks A and B will be used to develop a set of performance parameters, i.e., a means of rating the ability of a transducer to detect flaws based on the measurements made in Task A. This analysis will attempt to correlate the results of Task A with Task B to determine which of the measured properties have an effect on the response of a transducer to a defect.

APPENDIX C

COMPUTER PROGRAM FOR CORRELATION ANALYSIS

```
1 GO TO 100
4 GO TO 2270
8 GO TO 1170
12 GO TO 1370
16 GO TO 1830
20 GO TO 1100
24 GO TO 2860
28 GO TO 2910
32 GO TO 100
36 GO TO 2950
40 GO TO 2610
100 INIT
110 CALL "RATE",2400,0,2
120 F$=CHR(12)
130 F$=" "&F$
140 S$=CHR(13)
150 S$=" "&S$
160 DIM X(19,23),S1(19),S2(19),S3(19,23),P(19,23),R(19,23),R1(19)
170 DIM O$(150),R1(5),R3(5,23)
180 N7=19

190 REM NRD

200 DATA 0.312,0.375,0.312,0.375,0.25,0.25,0.312,0.25,0.25,0.25,0.1875
210 DATA 0.25,0.25,0.1875,0.25,0.312,0.1875,0.25,0.25,0.312,0.25,0.25
220 DATA 0.1875

230 REM NCF

240 DATA 2.25,2.25,2.25,2.25,2.25,2.25,2.25
250 DATA 5,5,5,5,5,5,5
260 DATA 10,10,10,10,10,10,10,10,10

270 REM ERA

280 DATA 0.0116,0.0287,0.0088,0.0106,0.0087,0.0091,0.0135
290 DATA 0.0183,0.0149,0.0108,0.0061,0.0154,0.0541,0.0032
300 DATA 0.0033,0.0184,0.0186,0.0314,0.0118,0.0074,0.0113,0.0024,0.0053

310 REM ACF

320 DATA 2.61,2.79,3.31,2.79,3.2,2.99,2.3
330 DATA 5.6,5.5,5.5,5.5,5.4,5.4,5.4
340 DATA 10.9,7.7,10.3,6,6.6,8.5,8.5,10.5,7.1

350 REM LSR

360 DATA -37.1,-78.1,-60.5,-54.6,-60,-74.3,-45.4
370 DATA -41.7,-56.9,-41,-42.5,-39.3,-35.4,-52.8
380 DATA -40.4,-45.6,-78.6,-50.3,-65.4,-45.1,-40.4,-52.7,-40

390 REM FBH

400 DATA -53.7,-74.5,-77,-75.5,-80,-84.8,-70.3
410 DATA -55,-63.8,-61,-67.6,-54.2,-52.2,-74.6
420 DATA -50.9,-63,-100,-74.4,-79.8,-69.4,-80.4,-62.4,-59.2

430 REM EDM
```

```
440 DATA -62.8,-71.2,-64.6,-71.5,-82.1,-83.9,-72.4
450 DATA -56.9,-69.9,-63.3,-53.3,-54.9,-59.5,-70.9
460 DATA -47.7,-65.9,-100,-79.6,-82.2,-68.5,-61.3,-68.3,-69.2

470 REM LCF

480 DATA -72.5,-100,-100,-100,-100,-100,-83.5
490 DATA -66.8,-78.7,-64.7,-72.5,-63.6,-70.5,-78.3
500 DATA -57.7,-65.5,-100,-68.3,-100,-70,-73.2,-68.8,-61.6

510 REM HCF

520 DATA -73.6,-100,-100,-100,-100,-100,-83.5
530 DATA -75.1,-100,-78.5,-78.1,-71.8,-72.4,-79.5
540 DATA -62.4,-81,-100,-82.4,-100,-78.6,-78.9,-78.3,-71.1

550 REM DMP

560 DATA 5,13,12,9,14,14,8,5,9,5,3,5,3,4,9,4,4,3,3,4,5,12,5

570 REM SSR

580 DATA 0.1,0.67,0.04,0.06,0.13,0.07,0.04
590 DATA 0.58,0.57,0.03,0.05,0.78,0.01,0.05
600 DATA 0.01,0.15,0.19,0.3,0.05,0.1,0.18,0.01,0.09

610 REM SIR

620 DATA 0.04,0.46,0.04,0.05,0.13,0.08,0.05
630 DATA 0.28,0.27,0.11,0.05,0.33,0.08,0.1
640 DATA 0.1,0,0.32,0.04,0.52,0,0,0,0

650 REM BWR

660 DATA 0.58,0.43,0.55,0.75,0.38,0.37,0.52
670 DATA 0.45,0.33,0.6,0.8,0.46,0.72,0.5
680 DATA 0.31,0.52,0.87,0.92,0.64,0.68,0.66,0.78,1.35

690 REM FFR

700 DATA 0.47,0.75,0.55,0.45,0.74,0.47,0.4
710 DATA 0.59,0.43,0.6,0.77,0.61,0.79,0.62
720 DATA 0.39,0.47,0.82,0.95,0.5,0.46,0.94,0.63,1.07

730 REM BWE

740 DATA 0.57,0.11,0.42,0.85,0.19,0.23,0.64,0.03,0.17,0.37,0.36,0.18
750 DATA -0.38,0.94,1.48,0.88,-0.16,0.46,1.2,1.71,0.72,2.11,1.26

760 REM CFE

770 DATA 0.16,0.24,0.47,0.24,0.42,0.33,0.02
780 DATA 0.12,0.1,0.1,0.1,0.08,0.08,0.08
790 DATA 0.09,0.23,0.03,0.4,0.34,0.15,0.15,0.05,0.29

800 REM BSR

810 DATA 0.16,0.03,0.08,0.02,0.03,0.04,0.12,0.1,0.09
820 DATA 0.17,0.04,0.15,0.09,0.12,0.26,0.28,0.5,0.14,0.52
```

```
830 DATA 0.06,0.02,0.12,0.04

840 REM BIR

850 DATA 0.12,0,0,0,0,0,0,0,0,0.06,0,0,0,0
860 DATA 0,0.01,0.3,0,0.26,0,0,0,0

870 REM RATING

880 DATA -2,-40,-26,-18,-24,-36,-6
890 DATA -4,-18,-3,-4,-2,-6,-15
900 DATA -4,-9,-47,-15,-24,-10,-12,-16,-5
910 READ X

920 REM MENU

930 PAGE
940 PRINT "DATA IS ENTERED."
950 GO TO 970
960 PAGE
970 PRINT "HIT USER DEFINABLE KEY ACCORDING TO FOLLOWING SELECTION LIST"
980 PRINT "1--DATA LIST"
990 PRINT "2--AVERAGE AND STANDARD DEVIATION"
1000 PRINT "3--ZERO ORDER LINEAR CORRELLATION COEFFICIENTS"
1010 PRINT "4--PARTIAL CORRELLATION COEFFICIENTS"
1020 PRINT "5--CORRECTION FOR SIZE AND FREQUENCY"
1030 PRINT "6--CORRECTION OF RATING FOR FREQUENCY"
1040 PRINT "7--CORRECTION OF RATING FOR EFFECTIVE RADIATING AREA"
1050 PRINT "8--INITIAL DATA"
1060 PRINT "9--CALCULATION OF RATINGS AND CORRELLATION"
1070 PRINT "10-PRINT ABBREVIATION TABLE"
1080 END

1090 REM CORRECTION FOR SIZE AND FREQUENCY (5-9)

1100 FOR I=1 TO 23
1110      FOR J=5 TO 9
1120           X(J,I)=X(J,I)-40*LGT(X(3,I))+20*LGT(X(4,I))
1130      NEXT J
1140 NEXT I
1150 GO TO 960

1160 REM AVERAGE AND STANDARD DEVIATION CALCULATION

1170 PRINT @40,12:F$
1180 N8=1000
1190 GOSUB 2230
1200 N8=300
1210 PRINT @40,12:"VARIABLE","AVERAGE","STD. DEV."
1220 GOSUB 2230
1230 S2=0
1240 S1=0
1250 S3=0
1260 FOR J=1 TO N7
1270      FOR I=1 TO 23
1280           S1(J)=S1(J)+X(J,I)
1290           S2(J)=S2(J)+X(J,I)^2
1300      NEXT I
1310      PRINT @40,12: USING 2190:J,S1(J)/23,SQR(S2(J)/23-(S1(J)/23)^2)
1320      GOSUB 2230
```

```
1330      S2(J)=SQR(S2(J)/23-(S1(J)/23)^2)
1340 NEXT J
1350 S1=S1/23
1360 GO TO 960

1370 REM CORRELLATION COEFFICIENTS

1380 FOR J=1 TO N7
1390      FOR I=J TO N7
1400           FOR K=1 TO 23
1410                S3(J,I)=S3(J,I)+X(J,K)*X(I,K)
1420           NEXT K
1430      NEXT I
1440 NEXT J
1450 S3=S3/23
1460 PRINT @40,12:F$
1470 N8=900
1480 GOSUB 2230
1490 N8=300
1500 M$="               ACF    LSR    FBH    EDM    LCF    HCF"
1510 N$="   DMP    SSR    SIR    BWR    FFR    BWE    CFE    BSR    BIR    RAT"
1520 O$=M$&N$
1530 P$="ERA"
1540 PRINT @40,12:M$;N$
1550 GOSUB 2230
1560 FOR J=1 TO N7-1
1570      IF J<3 THEN 1650
1580      IF J=3 THEN 1600
1590      P$=SEG(O$,(J-2)*6+1,3)
1600      PRINT @40,12:"      ";P$;"   ";
1610      IF J=3 THEN 1650
1620      FOR I=4 TO J
1630           PRINT @40,12:"        ";
1640      NEXT I
1650      FOR I=J+1 TO N7
1660           P(J,I)=S3(J,I)-S1(I)*S1(J)
1670           R(J,I)=P(J,I)/S2(I)/S2(J)
1680           IF J<3 THEN 1700
1690           PRINT @40,12: USING 2200:R(J,I)
1700      NEXT I
1710      IF J<3 THEN 1750
1720      GOSUB 2230
1730      PRINT @40,12:
1740      GOSUB 2230
1750 NEXT J
1760 FOR J=2 TO N7
1770      FOR I=1 TO J-1
1780           R(J,I)=R(I,J)
1790      NEXT I
1800 NEXT J
1810 GO TO 960

1820 REM PARTIAL CORRELLATION COEFFICIENTS

1830 PRINT @40,12:F$
1840 FOR J=1 TO 900
1850 NEXT J
1860 PRINT @40,12:"VARIABLES","PARTIAL CORRELLATION COEFFICIENTS"
1870 GOSUB 2230
1880 PRINT @40,12:S$
```

```
1890 GOSUB 2230
1900 G$="7      .8      .9      .10      .11      .12      .13      .14      .15"
1910 H$="                       .1      .2      .3      .4      .5      .6      ."
1920 J$="     .16"
1930 PRINT @40,12:H$;G$;J$
1940 FOR I=1 TO 15
1950      FOR J=I+1 TO 16
1960           R1=1
1970           FOR K=1 TO 16
1980                IF K=I OR K=J THEN 2000
1990                R1(K)=(R(I,J)-R(I,K)*R(J,K))/SQR((1-R(I,K)^2)*(1-R(J,K)
2000           NEXT K
2010           PRINT @40,12: USING 2210:I,J,R(I,J),R1
2020           IF I=5 AND J=7 THEN 2050
2030           IF I=13 THEN 2050
2040           GO TO 2130
2050           GOSUB 2230
2060           PRINT @40,12:F$
2070           FOR J1=1 TO 900
2080           NEXT J1
2090           PRINT @40,12:H$;G$;J$
2100           FOR J1=1 TO 400
2110           NEXT J1
2120           J=9
2130      NEXT J
2140      GOSUB 2230
2150      PRINT @40,12:S$
2160      GOSUB 2230
2170 NEXT I
2180 GO TO 960
2190 IMAGE 3X,2D,11X,2(2E,8X)
2200 IMAGE 3D.2D,S
2210 IMAGE 3X,2D,1X,2D,,2X,17(2D.3D,1X)

2220 REM PRINTER DELAY

2230 FOR J7=1 TO N8
2240 NEXT J7
2250 RETURN

2260 REM DATA PRINTOUT

2270 PRINT @40,12:F$
2280 N8=1500
2290 GOSUB 2230
2300 N8=300
2310 G$="XDC   NRD   NCF   ERA   ACF   LSR   FBH   EDM   LCF   HCF"
2320 J$="   DMP   SSR   SIR   BWR   FFR   BWE   CFE   BSR   BIR   RAT"
2330 PRINT @40,12:G$;J$
2340 GOSUB 2230
2350 I$="A"
2360 I7=0
2370 FOR I=1 TO 23
2380      PRINT @40,12:I$;"-";
2390      PRINT @40,12:I-I7;" ";
2400      FOR J=1 TO N7
2410           IF J>4 AND J<11 THEN 2450
2420           IF J=19 THEN 2450
2430           PRINT @40,12: USING 2580:X(J,I)
2440           GO TO 2460
```

```
2450            PRINT @40,12: USING 2590:X(J,I)
2460       NEXT J
2470       PRINT @40,12:S$
2480       GOSUB 2230
2490       I$="A"
2500       IF I<7 THEN 2560
2510       I$="B"
2520       I7=7
2530       IF I<14 THEN 2560
2540       I$="C"
2550       I7=14
2560 NEXT I
2570 GO TO 960
2580 IMAGE   3D.2D,S
2590 IMAGE   5D,X,S

2600 REM ABBREVIATION TABLE

2610 PAGE
2620 PRINT "XDC--TRANSDUCER"
2630 PRINT "NRD--NOMINAL RADIATING DIAMETER"
2640 PRINT "NCF--NOMINAL CENTER FREQUENCY"
2650 PRINT "ERA--EFFECTIVE RADIATING AREA"
2660 PRINT "ACF--ACTUAL CENTER FREQUENCY"
2670 PRINT "LSR--LOOP SENSITIVITY RATIO"
2680 PRINT "FHB--FLAT BOTTOM HOLE"
2690 PRINT "EDM--ELECTRIC DISCHARGE MACHINE"
2700 PRINT "LCF--LOW CYCLE FATIGUE"
2710 PRINT "HCF--HIGH CYCLE FATIGUE"
2720 PRINT "DMP--DAMPING"
2730 PRINT "SSR--SPECTRUM SYMMETRY RATIO"
2740 PRINT "SIR--SPECTRUM INFLECTION RATIO"
2750 PRINT "BWR--BANDWIDTH RATIO"
2760 PRINT "FFR--FAR FIELD RATIO"
2770 PRINT "BWE--BEAMWIDTH ERROR RATIO"
2780 PRINT "CFE--CENTER FREQUENCY ERROR"
2790 PRINT "BSR--BEAM SYMMETRY RATIO"
2800 PRINT "BIR--BEAM INFLECTION RATIO"
2810 PRINT "RAT--RATING BASED ON PARAMETERS"
2820 PRINT "HIT RETURN TO CONTINUE"
2830 INPUT A$
2840 GO TO 960

2850 REM CORRECTION OF RATING FOR FREQUENCY

2860 FOR I=1 TO 23
2870       X(19,I)=X(19,I)+LGT(X(4,I)/10)*20
2880 NEXT I
2890 GO TO 960

2900 REM CORRECTION OF RATING FOR SIZE

2910 FOR I=1 TO 23
2920       X(19,I)=X(19,I)+40*LGT(X(3,I)*100)
2930 NEXT I
2940 GO TO 960

2950 REM AVERAGE CORRELATION OF PARAMETERS TO FLAW RESPONSE

2960 R1=0
```

```
2970 FOR J1=6 TO 9
2980       R1(1)=R1(1)+R(J1,5)
2990       R1(2)=R1(2)+R(J1,12)
3000       R1(3)=R1(3)+R(J1,16)
3010       R1(4)=R1(4)+R(J1,15)
3020       R1(5)=R1(5)+R(J1,18)
3030 NEXT J1
3040 R1=R1/4
3050 R1=ABS(R1)
3060 R3=0

3070 REM CALCULATION OF RATING

3080 FOR I=1 TO 23
3090       R3(1,I)=X(5,I)+40
3100       R3(2,I)=-X(12,I)/0.064
3110       R3(3,I)=(0.09-X(16,I))/0.04
3120       R3(4,I)=-X(15,I)/0.27
3130       IF X(15,I)>0 THEN 3150
3140       R3(4,I)=-9*R3(4,I)
3150       R3(5,I)=-X(18,I)/0.018
3160 NEXT I

3170 REM CALCULATION OF AVERAGES

3180 S1(19)=0
3190 S2(19)=0
3200 FOR I=1 TO 23
3210       X(19,I)=0
3220       FOR J=1 TO 5
3230            X(19,I)=X(19,I)+R3(J,I)*R1(J)
3240       NEXT J
3250       S1(19)=S1(19)+X(19,I)
3260       S2(19)=S2(19)+X(19,I)^2
3270 NEXT I
3280 S1(19)=S1(19)/23
3290 S2(19)=SQR(S2(19)/23-S1(19)^2)

3300 REM CALCULATION OF CORRELLATION COEFFICIENTS

3310 J=19
3320 FOR I=3 TO 18
3330       S3(J,I)=S3(J,I)+R3(1,I)*X(5,I)+R3(2,I)*X(12,I)+R3(3,I)*X(16,I)
3340       S3(J,I)=S3(J,I)+R3(4,I)*X(15,I)+R3(5,I)*X(18,I)
3350 NEXT I
3360 S3(J,I)=S3(J,I)/23
3370 FOR I=6 TO 9
3380       P(19,I)=S3(19,I)-S1(19)*S1(I)
3390       R(19,I)=P(19,I)/S2(19)/S2(I)
3400 NEXT I
3410 PRINT @40,12:"      FBH","      EDM","      LCF","      HCF"
3420 PRINT @40,12: USING 3440:R(19,6),R(19,7),R(19,8),R(19,9)
3430 GO TO 960
3440 IMAGE 4(5X,3D.2D,5X)
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APPENDIX D

DEFINITION OF TRANSDUCER CHARACTERIZATION AND RATING PARAMETERS

APPENDIX D

DEFINITION OF TRANSDUCER CHARACTERIZATION AND RATING PARAMETERS

Definitions of the 12 transducer characterization parameters and the five rating parameters developed in the present program are as follows:

A. RF Characteristics

Six of the parameters describe characteristics of the RF power spectrum and RF waveform.

The center frequency (CF) is defined as the average of the frequencies (upper and lower) at which the power spectrum amplitude is half of maximum value (-6dB), i.e.,

$$CF = \frac{F_l + F_u}{2} , \tag{D1}$$

where F_l is lower frequency and F_u is upper frequency.

The center frequency error (CFE) is calculated by dividing the difference between the center frequency and the nominal, or nameplate frequency (NF), by the nominal frequency, i. e.

$$CFE = \frac{CF - NF}{NF} . \tag{D2}$$

The bandwidth indicates the range of frequencies over which the transducer operates between the -6dB points. The bandwidth ratio (BWR) is defined[6] as the 6 dB width of the spectrum divided by the center frequency, i. e.

$$BWR = \frac{F_u - F_l}{CF} . \tag{D3}$$

Spectrum symmetry refers to the balance in frequency distribution about the central frequency measured within the bounds of the bandwidth (BW). The spectrum symmetry ratio (SSR) is defined[6] by

$$SSR = \frac{4CF - F_1 - F_2 - F_3 - F_4}{2BW} , \tag{D4}$$

where F_1, F_2, F_3, and F_4 are the upper and lower frequencies at -12 dB and -20 dB points of the power spectrum.

Spectral inflection measures the singularity of the center frequency for those cases where the electrical tuning is not correct and two resonance peaks are created. The spectrum inflection ratio (SIR) is defined[6] as the ratio of the amplitude (A_I) in the "valley" between the resonance peaks where the spectrum slope reverses and the maximum amplitude (A_C) of the spectrum, (see Figure 5, pg. 13 in main body of report) i.e.

$$SIR = \frac{A_I}{A_C} \quad . \tag{D5}$$

The damping factor for a transducer is the number of cycles in the ultrasonic pulse train produced by the initial electrical pulse. This determines the lower resolution limit for the transducer. The damping factor (DMP) is obtained from the RF waveform by counting the number of cycles with an amplitude that is at least 10% of the maximum amplitude.

B. Ultrasonic Beam Characteristics

Five of the performance parameters were defined to describe the geometric characteristics of the ultrasonic beam produced by each transducer.

The far field maximum point (Y_o^+) is the focal point of the transducer. On the distance-amplitude plot, the far field maximum point is determined as shown in Figure 4. A theoretical value for this point can be calculated from the formula

$$Y_o^+ = \frac{d^2 - \lambda^2}{4\lambda} \quad , \tag{D6}$$

where d is the transducer diameter and λ is the ultrasonic wavelength in the test medium. The far field ratio (FFR) is defined as the ratio of the experimental to the theoretical values of this point.

In the far field region, the ultrasound radiating from the transducer is a well-defined beam. Thus, a beamwidth can be measured which is indicative of geometrical losses due to divergence and transducer size. The beamwidth error (BWE) is the deviation of the measured beamwidth from the theoretical beamwidth of a piston source. The experimental beamwidth (EBW) is measured from the beam profile plots. The theoretical beamwidth (TBW) is calculated from the formula

$$TBW = PL \left[\tan \left(\sin^{-1} \frac{0.51\lambda}{d} \right) \right] \quad , \tag{D7}$$

where PL is the ultrasonic path length. The beamwidth error is then calculated[6] from

$$BWE = \frac{TBW - EBW}{TBW} \quad . \tag{D8}$$

An effective diameter ratio (EDR) can be calculated by inverting Equation (D7) to give

$$EDR = \frac{0.51 \lambda}{d \left[\sin \left(\tan^{-1} \frac{EBW}{PL} \right) \right]} \quad . \tag{D9}$$

Beam symmetry about the center of the beam is found by measuring the beam center at -6 dB (BC_6), -12 dB (BC_{12}), and -20 dB (BC_{20}) of maximum amplitude. The beam symmetry ratio (BSR) is defined relative to the beam width at -6dB (BW_6) by the formula

$$BSR = \frac{2 \; (BC_6 - BC_{12} - BC_{20})}{BW_6} \quad . \tag{D10}$$

Beam inflection indicates the presence of undesirable side lobes in the beam. The beam inflection ratio (BIR) is defined as the ratio of the amplitude at the inflection point (A_I) and the amplitude at beam center (A_C), i.e.

$$BIR = \frac{A_I}{A_C} \quad . \tag{D11}$$

C. Conversion and Noise Characteristics

Two additional performance parameters were defined to characterize conversion efficiency and electrical noise.

The loop sensitivity is used to measure the conversion efficiency of a transducer. The loop sensitivity ratio (LSR) is defined as the logarithm (in dB) of the ratio of the initial pulse (V_T) applied at the transducer and the return echo (V_E) from a parallel flat surface, i.e.

$$LSR = -20 \, Log_{10} \frac{V_T}{V_E} \quad . \tag{D12}$$

The noise ratio (NR) is defined[6] in terms of the background noise level (BNL) and the transducer noise level (TNL) by the formula

$$NR = \frac{TNL - BNL}{BNL} \quad . \tag{D13}$$

The background noise level is measured with a 50 ohm dummy load in place of the transducer. The noise ratio must be calculated at a specific time after the electrical pulse. Two noise ratios were calculated for each transducer at 2 and 10 μseconds after the initial pulse leading edge.

D. Flaw Characterization

To describe the flaw response of the transducers, a flaw response ratio parameter (FRR) was defined as the logarithm of the ratio (in dB) of the initial pulse amplitude to the flaw echo amplitude

$$FRR = -20 \; Log_{10} \frac{V_T}{V_{e(flaw)}} \quad . \tag{D14}$$

A separate flaw response ratio (FRR) was measured for each flaw, with each transducer.

E. Performance Rating Parameters

The loop sensitivity rating is defined by

$$\text{LS Rating} = LSR + 35 \quad , \tag{D15}$$

where LSR is loop sensitivity ratio and 35 is the upper bound of the 99% confidence interval for the LSR from Table VI.

The center frequency rating is defined by the formula

$$\text{CF Rating} = -CFE/0.07 \quad , \tag{D16}$$

where CFE is the center frequency error and the divisor is 1/5 of the upper bound of the 99% confidence interval from Table IV.

The beamwidth error rating is defined by the formula

$$\text{BW Rating} = \begin{cases} -BWE/0.27, & BWE > 0 \\ BWE/0.03, & BWE < 0 \end{cases} \quad . \tag{D17}$$

Where BWE is beamwidth error and the divisors are 1/5 of the upper and lower bounds of the 99% confidence interval from Table V.

The spectrum inflection rating is defined by the formula

$$\text{SI Rating} = -\text{SIR}/0.07 \quad , \tag{D18}$$

where SIR is the spectrum inflection ratio and the divisor is 1/5 of the upper bound of the 99% confidence interval for SIR from Table IV.

The beam inflection rating is defined by the formula

$$\text{BI Rating} = -\text{BIR}/0.03 \quad , \tag{D19}$$

where BIR is beam inflection ratio and the divisor is 1/5 of the upper bound of the 99% confidence interval for BIR from Table V.

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